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Control Panel Dimensions for Gloved Operation
Study II: Toggle Switches
Minimum Spacing Required Between Toggle

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This study was to confirm the military specification of toggle switch spacing for gloved operators. An examination of toggle switch operations with five different glove types was conducted: a butyl and cotton glove assembly, a butyl and nomex glove assembly, a leather and wool glove assembly, a fire-fighting glove, and a vinyl glove. Subjects were required to operate a sequence of four switches in a 3 by 3 array. Three switch spacings were investigated: 15 mm, 20 mm, and 25 mm. Half the subjects operated toggle switches located directly in front of them, and the other half operated switches located behind them, in a position where the switches could not be seen. Subjects were required to activate the toggle switches in specific sequences as quickly and as accurately as possible. The task was machine-paced, and the time allowed for operation of a sequence of switches became progressively shorter as the subject was able to continue correct operation. Each subject performed the task both gloved and bare-handed.

Toggle switches spaced 25 mm apart yielded the fastest and most accurate performance, both bare-handed and with all gloves and glove assemblies. Operation of the back panel toggle switches by touch alone was slower and less accurate than the operation of the front panel switches. Gloved male subjects were able to operate the switches at faster speeds than gloved female subjects. The bulkier glove assemblies degraded bare-handed performance more than assemblies with little bulk and great tenacity. The worst performance occurred when the operator wore a bulky glove and operated back panel toggle switches spaced only 15 mm apart.

An increase in the military toggle switch spacing standard to at least 25 mm for operation with bulky handwear is recommended. If possible, glove bulk should be kept to a minimum. Glove snugness and high tenacity may enhance gloved toggle switch operation performance, particularly if the glove is bulky.

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INTRODUCTION

The U.S. Army has standard configurations for work environments designed to minimize factors that degrade performance or increase errors (military standard [MIL-STD] 1472D, 1989). The Army also requires that all military systems be designed so that physical and cognitive work loads, time constraints, and accuracy requirements do not exceed the capabilities of the human operator.

When a tactical situation demands that an operator wear gloves, achievement of an objective becomes more difficult. Because of increased bulkiness and diminished sensation, gloves often impede operating controls. Consequently, the Army has required controls to be compatible with using protective hand wear (MIL-STD-1472D, 1989). Control dimension standards developed for operation with bare hands must be revised for using gloves or mittens. Experimental details for such revisions have not been determined for many military workstations. This experiment was designed to provide such information. This study was the second of four studies sponsored by the Human Research and Engineering Directorate of the U.S. Army Research Laboratory. These studies investigate the performance of gloved operators using a variety of man-machine interfaces. *In this experiment*, gloved operation of toggle switches was examined.

Toggle Switch Studies

There are few published studies investigating the operation of toggle switches. Bradley and Wallis (1959 & 1960) compared three types of toggle switches, varying the spacing between switches, the orientation of the linear array, and the direction of throw. Two of the switches were standard size, while the third was a miniature switch. The dimensions of these switches and their vertical throw resistance are shown in Table 1. The researchers found a significant effect for all variables but were unable to attribute performance differences to any one switch characteristic. Mean operation time, percent touching errors, and percent operation errors generally decreased as the spacing between toggle switch centers increased from 5/8 in. to 1 in. However, Bradley and Wallis suggested that most errors were related to differences in throw resistance. The authors found resistance to operation to be positively correlated with operation time and touching errors, and negatively correlated with operation errors. They recommended that toggle switches of small dimensions and large resistance to operation be used when many switches have to be packed into a small area.

Table 1

Dimensions and Resistance of the Toggle Switches Studied by Bradley and Wallis (1959)

Switch	Arm diameter	Arm length	Off position	Resistance
1	16/64 in	50/64 in.	0°	6.6 oz
2	15/64 in	46/64 in.	20°	15.2 oz
3	8/64 in	18/64 in.	20°	34.2 oz

Toggle Switch Design Recommendations

General Guidelines for Toggle Switches

Despite the lack of published toggle switch studies, several authors of ergonomic handbooks have made design recommendations for their use in workstations. Chapanis and Kinkade (1972) advised including toggle switches in the design of control panels. Since only a small amount of space is required for them, they could be operated quickly and simultaneously with other toggle switches in a row. They added that toggle switches can also be easily identified by their proximity to an associated display or their location in an array. The authors recommended that toggle switches be built with elastic resistance that initially increases and then decreases as the desired position is approached. Such elastic resistance provides cues to switch displacement which are independent of control velocity and acceleration. With elastic resistance, the control returns automatically to the null position when the hand is removed. Elastic resistance has the additional advantage of allowing the control to snap into position without stopping between positions, permitting quick changes to be made in the direction of control movement, and allowing the hand to rest on the control without activating it. This decreases the likelihood of undesired activation. Chapanis and Kinkade (1972) recommended that toggle switches be installed vertically. The horizontal orientation should be used only if required for consistency with the orientation of a display function or to prevent accidental operation. An audible click should be provided to indicate activation. Mounting toggle switches in a horizontal array enhances speed and ease of operation. Vertical arrays require larger spaces between switches (Chapanis & Kinkade, 1972; Ivergard, 1989).

The current standards of the U.S. military are in agreement with the previous recommendations (MIL-STD-1472D, 1989). Toggle switches are to be used for functions involving two discrete positions or when space limitations are severe. Toggle switches with three positions are only to be used when another type of discrete control is not feasible or when the toggle switch is of the spring-loaded, center position-off type. Three-position toggle switches of the latter type are not to be used if release from the spring-loaded position results in switch handle travel beyond the off position. The U.S. military also requires toggle switches to gradually increase throw

resistance, followed by a drop in resistance when the switch snaps into position. Additional standards for toggle switches include (a) no possible stop between positions, (b) an indication of control activation such as a click or an associated integral light, and (c) a vertical orientation with the "off" in the down position. Horizontal actuation is only to be employed when necessary for compatibility with the control function or equipment location.

U.S. military standards were also designed to prevent accidental actuation. Channel guards, lift-to-unlock switches, or other equivalent prevention mechanisms are to be used when inadvertent activation would be hazardous. Safety wire or lock wire is prohibited. The resistance of lift-to-unlock mechanisms must not exceed 13 Newtons (3 lb) and the location of a cover guard should not interfere with operating the protected switch or adjacent controls.

Specific Guidelines for Location of Adjacent Toggle Switches

There is a consensus in ergonomics handbooks concerning the location of adjacent toggle switches (Eastman Kodak Company, 1986; Ivergard, 1989; MIL-STD-1472D, 1989): (a) Random one-finger operation of toggle switches requires a minimum distance between switch centers of 20 mm (3/4 in.), the optimum distance is 50 mm (2 in.); (b) sequential one-finger operation of toggle switches requires a minimum distance between centers of at least 12 mm (1/2 in.), while the desirable distance is 25 mm (1 in); (c) when different fingers are used to operate the toggle switches, randomly or sequentially, the minimum distance between control centers is to be 16 mm (5/8 in), with a desirable distance of 20 mm (3/4 in.); (d) lever-lock toggle switches randomly operated with one finger are to have a minimum separation of 25 mm (1 in.) with an optimum separation of 50 mm (2 in.).

Specific Guidelines for Size, Displacement, and Resistance of Toggle Switches

Specific design guidelines have also been given for the size, displacement, and resistance of toggle switches (MIL-STD-1472, 1989; Ivergard, 1989): (a) The minimum arm length of a toggle switch is 12 mm (1/2 in.) for bare finger operation and 37 mm (1-1/2 in.) for operation with heavy hand wear; (b) the maximum arm length specified for both bare finger and heavy hand wear use is 50 mm (2 in); (c) recommended arm tip size is 3 mm (1/8 in.) as a minimum and 25 mm (1 in.) as an optimum size; (d) when a toggle switch is to be hand operated rather than finger operated, the minimum tip size is 12 mm (1/2 in.) and the optimum tip size is 50 mm (2 in); and (e) the minimum recommended displacement between positions for two position switches is 30° and the maximum 80°, and for three position toggle switches, 17°, 25°, and 40° are the desired minimum and maximum distances of travel per segment; and (f) the military standard for the resistance of a small toggle switch is 2.8 N (10 oz) minimum and 4.5 N (16 oz) maximum. For a large switch, the minimum resistance requirement is the same, while the maximum increases to 11 N (40 oz).

Only one author has investigated the effect of gloves on toggle switch operation. Bradley (1969a) studied the difference between bare-handed and gloved performance of instrument control operations. The subjects operated push buttons, toggle switches, a vertical lever, and a knob while bare-handed and while wearing a wool glove or a leather glove over a wool glove. Bradley's results indicated that operation time for the toggle switch

during the leather and wool glove combination condition was significantly less than that for the bare hand or the wool glove alone. The wool glove was inferior to the bare hand and the combination glove across all control types. The author suggested that the added padding and protection of the leather and wool glove combination allowed the user to operate the toggle switch with increased speed and force without fear of injury. Bradley additionally noted that the wool glove would slide easily on the smooth surface of the controls and did not fit snugly on the fingers. He concluded that the effect of gloves on control operation was dependent on the type of glove, physical characteristics of the control, and the type of control operation required.

Bradley conducted a second study (1969b) in which he investigated the effect of four glove characteristics--tenacity, snugness, protectiveness, and suppleness--on control operation time. He obtained objective measures and subjective ratings of the four characteristics on 18 different glove assemblies. Tenacity and efficiency of performance were highly correlated, which Bradley believed to be because of the method of operation of these controls. Glove snugness was also significantly correlated with operation time of on-off controls. Bradley explained that snugness increased the effect of slight finger movement. Additionally, suppleness and protectiveness were negatively correlated with each other, and when this correlation was significant, suppleness and protectiveness were oppositely correlated with operation time. Also, a significant negative correlation for snugness and suppleness was found for adjustable controls. Bradley stated that suppleness has no value in the operation of on-off controls, as these require minimal fine or extensive finger manipulations. Push-button controls were most sensitive to the glove effect, followed by the levers. The toggle switch and knob were the least affected controls. Bradley concluded that gloved efficiency of control operation depended on particular measurable glove characteristics and type of control operation. In general, (a) glove snugness will improve the operator's performance on most controls, (b) suppleness facilitates operation of adjustable controls, (c) protectiveness can be undesirable when suppleness is needed, and (d) tenacity is important with on-off switches.

Bradley's study investigated the operation of four control types, one at a time, and not the operation of a sequence of toggle switches in an array. This study did not specify distances between controls and did not address accidental activation of adjacent controls. Additionally, there were no studies that investigated the adequacy of the minimum spacing specifications between adjacent toggle switches for gloved operation. Although military standards specify toggle arm length for operation with heavy hand wear, information is not available concerning the minimum and optimum distances between switches.

The first study in the present series investigated the effect of gloves on push-button operation (Berkhout, Anderson, McCleerey, & Granaas, 1992). Six hand-wear conditions were studied: the bare hand, a butyl and nomex glove assembly, a butyl and cotton glove assembly, a leather and wool glove assembly, a fire-fighting glove, and a thin vinyl glove. The subjects performed both self-paced and machine-paced button-pushing tasks that involved a panel of nine buttons in a 3 by 3 array. Three different spacings between buttons were used. The results indicated push-button operation was faster when the buttons were 13 mm and 19 mm apart than when they were 25 mm apart. Subjects with larger hands tended to score faster times and make more

errors in the machine-paced task. It was concluded that the 13-mm spacing was adequate for operation by gloved operators. (For a comprehensive review of the literature concerning glove effects see Berkhout, Anderson, McCleerey, & Granaas, 1992).

The present study attempts to provide missing information regarding gloved operation of toggle switches. Five glove conditions were investigated that provided a continuum of hand wear ranging from a snug fitting, thin, single layer to multiple thick layers of great bulk. Subjects were required to flip four toggle switches in a specified sequence. The switches were mounted in a 3 by 3 array on three different panels with different distances between toggle switches. The panels of toggle switches were placed either in front and above the subject or behind and to the lower right side of the subject. In the latter position, the switches were not visible and operation of the correct switches was dependent upon tactile, kinesthetic, and auditory feedback.

Six hypotheses were tested: (a) The less bulky glove assemblies would be superior to the more bulky glove assemblies since fine finger manipulation was required to flip the correct toggle switches while avoiding activation of adjacent toggle switches; (b) the combination of the smallest spacing between switches and the bulkiest glove assemblies would result in the poorest performance; (c) because of the smooth and slippery surfaces of the metal toggle switches, gloves with greater tenacity would be superior to gloves with low tenacity; (d) performance with glove assemblies of little bulk and great tenacity would be superior to the bare hand as the tenacity of the bare hand is less and can further be decreased by perspiration; (e) performance would be impaired when the panel of toggle switches was located behind the subject because of lacking visual feedback; and (f) increased spacing between toggle switches would degrade performance of the bare hand and gloves of little bulk and great tenacity.

METHOD

Subjects

Sixty female and 60 male undergraduate students at the University of South Dakota served in this study. All experimental subjects signed a consent form (see Appendix A) and received extra course credit for their participation.

Subjects were stratified according to hand circumference within each gender. This was accomplished by dividing the hand circumference range of the Army's anthropometric survey (Gordon et al., 1989) into three equal subranges for each gender.

Males:	small	= 190-212 mm
	medium	= 213-222 mm
	large	= 223-237 mm
Females:	small	= 167-182 mm
	medium	= 183-190 mm
	large	= 191-207 mm

Each of the three ranges for each gender was represented by 20 subjects. Persons whose hands were outside this range were not used. Only right-hand, dominant individuals were studied. A comparison of the hand circumference measures of these subjects with Army personnel (Gordon et al., 1989) is shown in Table 2. Table 3 shows the percentiles of the Army anthropometric distribution that bound each hand circumference range, and it also shows the percentage of Army personnel that would be included in each hand size range used in this study.

Table 2

Comparison of Army Personnel and Study Subject's Hand Circumference Measurements (in mm)

			Percentile		
Group	Mean	*SD*	25th	50th	75th
Army					
Males	213.8	9.7	207.2	213.4	220.1
Females	186.2	8.5	180.4	186.0	191.6
Subjects					
Males	217.5	10.1	211.5	217.0	224.0
Females	187.3	9.2	180.0	187.0	193.5

Apparatus

Toggle Switch Panels

Three panels of toggle switches were used in this study. Each panel consisted of nine switches in a 3 by 3 array. The operation of a switch completely surrounded by other toggle switches, as well as the operation of switches in rows and columns could be required.

The toggle switches met all requirements specified by MIL-STD-1472D. They were two position, spring-loaded, lever-action switches that remained in the activated position as long as force was applied. The switches returned to the "off" position (the center position) when the operator's hand was removed. The switches were installed in a vertical orientation. Lever resistance increased with displacement and dropped when the switch was activated. The force needed to actuate each switch varied from 4.8 N to 5.6 N (17 to 20 oz). The switches were unable to stop between positions and had an audible click to indicate activation. The arm of the toggle switch was constructed of nickel-plated brass and was 50 mm long. The diameter of the control tip was 5 mm and there were 30° of displacement between positions (Carlingswitch, Inc., 1988, model number 6FA63-E3).

Table 3

Comparison of Army Personnel Hand Circumference Percentiles and Study Subject's Hand Circumference Ranges

Hand circumference range (mm)	Equivalent Army percentiles	Percentage of Army personnel
Males		
Small (190-212)	1st through 50th	50%
Medium (213-222)	50th through 80th	30%
Large (223-237)	80th through 99th	20%
Females		
Small (167-182)	1st through 35th	35%
Medium (183-190)	35th through 70th	35%
Large (191-207)	70th through 99th	30%

The three panels had different spacings between switches.

compressed panel = 15 mm between centers
standard panel = 20 mm between centers
expanded panel = 25 mm between centers

The standard panel complied with military recommendations for the layout of panels requiring random or sequential bare-handed operation of toggle switches by different fingers (MIL-STD-1472D, 1989). These three spacings were chosen to determine if gloved operation of toggle switches would be improved given a 25-mm distance between switches rather than the 20 mm specified for the bare hand or if panel dimensions could be reduced to 15 mm without impairing performance. Each wooden panel was 23 cm square with the array of toggle switches located in the center. The front panel was located directly over the computer monitor; the monitor was on top of a work surface, and the base of the panel was 48 mm from this work surface. The top of the panel was 105 cm from the seat reference point (SRP) at the lowest adjustable seat level and 92 cm from the SRP at the highest adjustable seat level. The maximum distance to the toggle switches from the seat reference vertical was 62 cm. This allowed the toggle switches to be within the functional arm reach boundaries for operating manual controls for 95% of the male or female population (Bullock, 1974, Woodson, 1981).

The base of the back panel was located 30 cm above the floor and approximately 105° to the right of the subject's sagittal plane with the left edge of the panel in direct alignment with the right edge of the computer screen. The distance between the front work surface and the wooden frame onto which the back panel was mounted was 16 in. This distance was the minimum space required to sit down at the work surface and get up from it (Woodson, 1981). The SRP of the chair to the floor had the adjustable range of 41.5 cm to 54.5 cm. Therefore, there was 11.5 cm from the lowest SRP to the bottom of the panel and 24.5 cm from the highest SRP to the bottom of the panel. The back panel of the toggle switches was within the functional reach boundaries for control operation for 95% of both genders (Bullock, 1974).

Computer Interface

The toggle switches were interfaced with the computer through an AT-compatible keyboard in the same manner as the previous study (Berkhout, Anderson, McCleerey, & Granaas, 1992). The software program included written instructions about the task and 96 diagrams that depicted the panel and the array of toggle switches with appropriately sized rectangles.

The rectangle that represented the panel was 120 mm by 73 mm. The rectangles that represented the nine toggle switches were 21 mm by 9 mm. On each diagram, four of the toggle switch rectangles were numbered one through four. Each diagram had different toggle positions numbered. An example of the diagrams is shown in Appendix B. These numbers indicated the toggle switches that the subject needed to flip and the order in which they should be flipped. They were approximately 4 mm by 3 mm. The numbers were white, the rectangles representing the toggle switches were black, and the color of the panel rectangle was light green.

The 96 diagrams had different sequences of toggle switches indicated by the numbers. The required sequence of switch closures ensured that all toggle switches appeared the same number of times in each of the four positions in the sequence. The diagrams were presented in a random order to each subject.

Although the operation of toggle switches in a single row could be a somewhat easier task than the operation of switches from differing rows, it was believed necessary to include such sequences in this study. It has been consistently recommended that toggle switches be mounted in horizontal arrays to enhance speed and ease of operation. Consequently, operation of switches in a single row would occur often if such recommendations were followed. Given the large number of diagrams and subjects in this study, the ease of operation of certain sequences of toggle switches would not significantly confound possible glove effects as these sequences would be randomly distributed among subjects. Before the presentation of each diagram, the computer presented the subject with the message, "Position your hand." Simultaneous with this message, a tone sounded. A diagram was presented 1 s later. The first diagram remained on the screen for 4.5 s. If the subject correctly flipped the sequence of four toggle switches indicated, the next diagram remained on the screen for 4.0 s, and the next diagram remained on the screen for 3.5 s. Provided the subject continued to flip the correct sequences of toggle switches, successive presentation times of diagrams were then reduced by 0.1 s. Pilot tests showed that the initial 4-second presentation time was more than adequate for subjects to flip the correct sequence of toggle switches. Once the presentation time of diagrams dropped below 3 seconds, this task became more difficult, making it necessary to decrease presentation times by 0.1 s steps, rather than 0.5 s.

The subject was given three opportunities to flip the correct sequence of toggle switches for each diagram presentation time. If the subject did not perform correctly, the next two diagrams remained on the screen for the same duration. If the subject were not able to flip the correct sequence of toggle switches when the third diagram was presented for that particular time frame, the trial ended. The diagram presentation time was shortened only after a correct response. Presentation time continued to be reduced until the subject failed to flip the correct sequence three times in a row for a particular time frame.

At the end of each presentation, a tone sounded to indicate that no more toggle switch activations would be accepted and that the subject should wait for the next hand-positioning message. The time between presentations was 5 s. At the fourth second of this interval, the subject received the hand-positioning message.

Gloves

The five different glove assemblies examined in this study provided a continuum of bulkiness. Three gloves studied were in current use by the Army: a butyl glove with a cotton liner, a butyl glove with a nomex liner, and a leather glove with a wool liner. A chemical-resistant vinyl glove which was less bulky than any of the military models, and a professional fire-fighting glove, which was somewhat more bulky than the three Army issue gloves, was studied.

Procedure

Investigation of Glove Characteristics

Before the experiment, the different glove assemblies were examined to determine differences in bulk, pliability (suppleness), and tenacity. Grip strength loss and degradation of tactile sensitivity was measured with each glove. Each assembly was weighed to the nearest gram. Pad thickness was measured using calipers on the ventral aspect of the fingertips and dividing this amount by 2.

A measure of pliability was obtained using the pendulum method devised by Bradley (1961). The middle finger of each glove was suspended from a clamp which held the glove firmly in position. The rigid arm of the pendulum, 945 mm long, was clamped to the glove finger leaving 10 mm of the glove exposed to serve as the hinge of the pendulum. A 125-g weight was attached to the pendulum arm. The arm was then released from a constant 45° angle from the horizontal plane of the pendulum hinge. The number of oscillations required for the arm to damp down to a constant angle of 70° was recorded (see Table 4). Although Bradley used a 1/2-in. strip of the middle finger of the glove for the pendulum hinge, the present study used the actual glove finger since it represented glove pliability more accurately and realistically. The ability of the glove to assume a position taken by the hand (i.e., pliability as defined by Bradley) is dependent upon the flexibility of both the dorsal and palm surfaces of the glove.

Bradley's (1961) method of measuring tenacity was also replicated. A 6-cm by 6-cm piece of the palm of each glove was weighted with a 651-g weight and dragged across a polished aluminum sheet (Mirro Corporation, item number C8411). The kinetic friction of the glove material slipping across this surface was recorded using an electronic digital scale.

To obtain information concerning differences in glove grip-strength degradation, pilot subjects squeezed a dynamometer with as much force as possible using a full hand grip while fully extending the arm perpendicular to the body. Bare-handed and gloved grip strength was measured three times, each with the order of these measures balanced across subjects.

Table 4

A Comparison of Glove Pliability

Glove type	Number of oscillations
Vinyl	39
Butyl and cotton	33
Butyl and nomex	22
Leather and wool	10
Fire-fighting	13

There was a 15-s intertrial interval to reduce fatigue effects. The means of the bare-handed and gloved grip-strength measures were compared; the percentage of this difference was used as an index of glove grip-strength degradation.

Glove tactile degradation differences were determined by measuring the pilot subjects' gloved 2-point thresholds via a Mackworth "V" test (Adolfson & Berghage, 1974). This test was constructed from two rigid metal straightedges fastened together at one end and widening to a 25-mm gap over a distance of 50 cm. Subjects moved their index fingers up and down the Mackworth "V" and reported when they could feel two separate sensations and when the two separate sensations became a single sensation, respectively. These measures were obtained three times with the order of the task balanced across subjects. The mean of the measures of the gloved 2-point threshold was used as an index of tactile degradation.

Grip strength and 2-point threshold measures were obtained from the same subjects. The subjects were randomly assigned to glove assemblies, and the order of the tests was balanced across subjects. Measures were only obtained on the subjects' right hands. Table 5 provides a summary of the glove-characteristic investigation findings.

Glove-Fitting Protocol

A standardized methodology for fitting gloves could not be found in literature. Glove sizes provided by the manufacturers were obviously based on different scales and dimensions. Therefore, a glove-fitting protocol was developed to ensure that the best possible fit for a particular glove assembly was obtained for every subject before testing (Berkhout, Anderson, McCleerey, & Granaas, 1992). The actual measurements used to establish the fitting protocol are shown in Appendix C, and the hand dimension ranges used to assign a glove size appear in Appendix D. Assignment of glove size to Army personnel based on hand circumference and wrist-to-index-finger centiles (Gordon et al., 1989) is shown in Table 6.

Table 5

A Comparison of Glove Characteristics

	Vinyl	Butyl and cotton	Butyl and nomex	Leather and wool	Fire-fighting
Weight (g)	11	83	110	91	155
Pad thickness (mm)	.5	1.25	2	2	2
Reduction in grip strength	.5%	19%	26%	37%	28%
2-point threshold (mm)	1.5	2.8	3.8	2.3	2.3
Pliability (ordinal scale)	1	2	3	5	4
Tenacity (g kinetic friction)	257.8	389.9	389.9	204.4	235.8

Army anthropometric data for third digit length were not available. For this study, subjects with hand sizes smaller than the glove measurements were assigned to the smallest glove available. As shown in Table 6, the Army and commercial gloves examined could not snugly fit Army population 5th through 95th percentiles. This is particularly evident for female subjects with smaller hand sizes.

Toggle Switch Experiment

Data were gathered about 60 subjects operating the front panel before gathering data about subjects operating the back panel.

The subject's hand circumference was measured at the time he or she volunteered to participate in the experiment. The subject then was stratified into the appropriate hand size group by gender and randomly assigned to a glove assembly. Just before participation in the experiment, the other hand measurements were obtained, and the subject was assigned to a glove size. The subject then donned the glove assembly and the index-finger-width measurement was obtained. Next, the subject adjusted the chair to an erect sitting height of 135 cm (from the floor to the top of the head). Because the distance between the shoulder pivot point and the head pivot point is equal to the

distance between the head pivot point and the top of the head (Diffrient, Tilley, & Harman, 1981), this constant erect sitting height allowed subjects of all sizes to perform the experimental task with their shoulders at the same level. Further, erect sitting height could be measured with more precision than shoulder pivot height, as the top of the head was more obvious and without musculature.

Table 6

Assignment of Glove Size by Hand Circumference and Wrist-to-Index Finger Percentiles

	Females		Males	
Glove Assembly	Hand Circumference	Wrist-to-Index Finger	Hand Circumference	Wrist-to-Index Finger
Butyl				
Small	0	70th-98th	75th-99th	20th-85th
Medium	0	97th-99th	80th-99th	70th-99th
Large	0	99th	0	85th-99th
Nomex				
8	70th-99th	97th-99th	1st-35th	75th-99th
9	70th-99th	99th	1st-35th	90th-99th
10	95th-99th	99th	5th-75th	97th-99th
11	0	0	35th-95th	35th-90th
Wool				
3	30th-90th	10th-65th	1st-5th	1st-5th
4	80th-99th	25th-90th	2nd-40th	2nd-50th
5	0	85th-99th	35th-95th	35th-90th
Leather				
2	97th-99th	1st-65th	1st-5th	1st-5th
3	0	30th-90th	35th-95th	3rd-55th
4	0	75th-99th	90th-99th	25th-85th
5	0	95th-99th	0	55th-97th
Fire-fighting				
Small	40th-97th	95th-99th	1st-15th	65th-98th
Medium	99th	95th-99th	20th-90th	65th-98th
Large	0	0	50th-98th	97th-99th
X Large	0	0	65th-99th	98th-99th

Once seated directly in front of the computer monitor, the subject was allowed to adjust the chair forward or backward to accommodate subjective comfort preferences. The distance of the chair from the monitor was not held constant as most workstations have chairs with adjustable ranges for this dimension. The subject then read the instructions on the computer screen; these instructions are shown in Appendix E.

Subjects began the experiment either bare-handed or wearing the assigned glove assembly. The order of hand-wear condition was balanced across subjects. The order of the compressed, standard, and expanded panels was also balanced across subjects. The subjects were not restricted as to which fingers to use on the toggle switches, but were allowed to develop their own method of operation. Although different response strategies add variability to the data, the experimental task was similar to actual Army tasks in which the operator must complete a particular configuration from a checklist. Thus, this was believed to be more representative of actual behavior of experienced operators in an Army work environment. The pilot subjects had been capable of developing efficient methods of operation by the end of their practice trials.

Each subject was given three initial practice trials. These practice trials were no different than the test trials. The subject was either gloved or bare-handed throughout the practice trials depending upon the assigned order of hand-wear condition. Additionally, all initial practice trials were performed on the same panel, the first panel of the assigned order. The subject was closely observed to ensure that the task was understood and performed as specified. The subject was also able to ask questions during this time, and further instructions could be given.

A performance criterion was established, which excluded those subjects who were unable to perform the task at the end of the initial three practice trials. This criterion (correct operation of at least one sequence of toggle switches) was intentionally lax as it was expected that the performance of the task with the bulkier glove assemblies and inefficient panel layouts would be quite difficult. Thus, it was necessary to exclude those individuals who did not demonstrate the ability to perform the task without eliminating those individuals with impaired performance because of the glove or panel. No subjects were excluded from the experiment when tested on the front panel. However, 4 subjects were excluded from the experiment when tested on the back panel. One of these subjects was not a native English speaker and was excluded because the instructions were not understood. Three potential subjects, 2 females and 1 male, appeared to understand the directions but were unable to follow them.

Subsequent to completing the three practice trials, the subject then was tested on the same panel during the same hand-wear condition. Next, the subject changed hand-wear conditions and performed one practice trial followed by one test trial on the same panel. This way, learning on one panel was maximized so glove effects could be better separated from learning effects. For the other two panels, the subject performed one gloved practice trial and one test trial, and one ungloved practice trial and a test trial in an assigned hand-wear order. The experimenter left the room during the trials, but entered the room at the end of every trial to make any changes in hand wear and panels. This ensured experimental conditions remained constant.

For the back panel trials, extended arm length was held constant, rather than erect sitting height. Each subject adjusted the chair so the tip of the third digit was even with the bottom of the panel. This allowed the toggle switches to be within the functional reach ready for control operation.

The subjects were instructed to perform the back panel task in the same way, except the toggle switches needed to be flipped up rather than down. The panel was mounted upside down as compared to the front panel. Because the same diagrams were used as when the panel was in front of the subject, the subject was required to cognitively invert the diagram viewed on the screen to determine the correct sequence of toggle switches on the back panel. Thus, the top row of toggle switches on the diagram corresponded to the bottom row of toggle switches on the panel, and the bottom row on the diagram corresponded to the top row on the panel. Left and right orientation remained the same. Mounting the back panel in this manner allowed the subject to use the same natural hand and arm movements that were used when the panel was mounted in front of the subject. Because the same motions would be used in operating the toggle switches on both the back and front panels, the back panel was easily learned by the subject, despite the cognitive inversion. Pilot subjects learned the task easily, and experimental subjects demonstrated no undue difficulty. Directions for the back panel task are in Appendix F. All other experimental conditions and procedures remained the same.

Experimental Design

A 5 (glove assembly) by 3 (spacing between toggle switches) by 2 (hand condition) by 2 (panel location) by 2 (gender) doubly multivariate analysis of variance (ANOVA) was used to analyze the data. The between-groups independent variable was the panel location, either in front of or behind the subject. The glove used was the within-group independent variable. Gender served as a blocking variable. Two repeated independent measures were (a) spacing between toggle switches (compressed, standard, and expanded), and (b) hand condition (gloved and bare).

Performance Measures

All diagram presentation times during a single trial were recorded as well as the specific switches each subject flipped. The best time score was the shortest diagram presentation time in which the subject could flip the correct sequence of four toggle switches. Each subject had six best time scores: a bare-handed and a gloved best time score for each of the three panels.

The accuracy of performance was assessed with two other dependent variables: errors-per-opportunity and mean time-of-error variances. The number of errors made while performing the task was a function of the subject's best time score and would not correctly reflect a subject's level of performance. Subjects who were able to perform the task at higher rates of speed would have greater opportunities to make errors since they would complete more trials. Conversely, subjects who were only capable of performing the task at low rates of speed completed fewer trials and had fewer opportunities to make errors.

The errors-per-opportunity dependent variable was defined as the number of error trials divided by the number of trials completed. An error trial occurred when the subject did not flip the correct toggle switch in the correct order. Trials in which time expired were not counted as error trials unless an incorrect toggle switch was activated. Each subject generated six errors-per-opportunity scores, gloved and bare-handed for each of the three panels.

The mean time-of-error dependent variable was defined as the mean of the time scores of all error trials in a given condition. The subjects generated a mean time-of-error score for each of the six conditions.

RESULTS

Bare-Handed Data Analysis

Subjects were randomly assigned to five groups, one for each glove type to be tested. In theory, random assignment should result in a close match of abilities and performance scores across the five groups when performing bare-handed. Before analyzing the gloved performance results, the bare-handed data were inspected to determine if the five groups were equal in performance abilities on this task. The three dependent measures were examined to determine how strongly they were correlated during bare-handed conditions. Pearson product-moment coefficients were obtained across all bare-handed data (see Table 7). Because of the high correlations found between these variables, a multivariate analysis of the data was performed.

A 5 (glove assembly) by 3 (toggle switch spacing) by 2 (panel location) by 2 (gender) doubly multivariate ANOVA was applied to the bare-handed data to determine if there were any differences between the groups assigned to the various gloves when they were performing bare-handed.

Wilks' Lambda was chosen as the criterion of statistical significance as it is more powerful than Pillai's criterion and is recommended as the criterion of choice when sample sizes are equal (Tabachnick & Fidell, 1989).

The main effect for panel location was significant ($F_{(3,98)} = 10.69$, $p < .002$) as well as the main effect for switch spacing ($F_{(6,95)} = 3.71$, $p < .002$). The main effects for gender and glove were not significant. The mean best time scores, errors-per-opportunity scores, and mean time-of-error scores for each panel location, switch spacing and gender are shown in Tables 8, 9, and 10 for each of the groups assigned to particular gloves. There was one significant interaction, assigned glove group by panel location ($F_{(12,160)} = 1.99$. $p < .02$), as shown in Figures 1 - 9. As shown in Figures 4, 5, and 6, the group assigned the butyl and nomex glove had greater differences in bare-handed errors-per-opportunity scores between the front and back panel locations than the other glove groups. Upon inspection of the data, two outliers were found, 1 male and 1 female subject. The female subject's errors-per-opportunity scores for the three respective toggle switch spacings were 0.75, 1.00, and 0.56. Comparatively, the means of this group (female--buytl and nomex) were 0.19 for the compressed spacing, 0.31 for the standard spacing, and 0.17 for the expanded spacing.

The male subject's errors-per-opportunity score for the compressed toggle switch spacing was 1.00. In contrast, the group (male--buytl and nomex) mean for the compressed panel was 0.28. This subject's other scores did not differ markedly from the group means for the standard and expanded spacings. When these two outliers were removed from the data analysis, the Glove x Position interaction was no longer significant and the other interactions remained insignificant as well. Thus, upon removal of the outlier scores, there were no differences between glove assembly groups. The only differences between groups that were found were expected (panel location and toggle switch spacing). Consequently, the bare-handed scores were not used as a covariate in this data analysis.

Table 7

Pearson Product-Moment Correlation Coefficients of Bare-Handed Dependent Measures

	Best Time Scores			Errors per Opportunity			Mean Time of Errors		
	Compressed	Standard	Expanded	Compressed	Standard	Expanded	Compressed	Standard	Expanded
Best time scores									
Compressed	1.00	.40	.54	.61	.20	.35	.34	.15	.05
Standard	.40	1.00	.39	.24	.55	.13	.18	.31	-.08
Expanded	.54	.39	1.00	.27	.06	.53	.26	-.01	.18
Errors-per-opportunity scores									
Compressed				1.00	.32	.30	.62	.16	-.04
Standard				.32	1.00	.10	.20	.56	-.05
Expanded				.30	.10	1.00	.20	.04	.64
Mean time-of-errors score									
Compressed							1.00	.15	.05
Standard							.15	1.00	.01
Expanded							.05	.01	1.00

Table 8

Mean Bare-Handed Best Time Scores and Standard Deviations (in seconds) for Each Glove Assembly and Toggle Switch Spacing

Glove assembly	Front Panel Compressed	Front Panel Standard	Front Panel Expanded	Back Panel Compressed	Back Panel Standard	Back Panel Expanded
Butyl and cotton						
Females	1.90 (.34)	2.52 (1.01)	2.02 (.21)	2.10 (.17)	2.13 (.29)	2.13 (.27)
Males	1.97 (.31)	1.88 (.38)	1.83 (.48)	2.83 (.42)	2.78 (.85)	2.48 (.76)
Butyl and nomex						
Females	1.90 (.25)	1.93 (.39)	1.80 (.26)	2.43 (1.03)	2.82 (1.00)	2.42 (.58)
Males	2.22 (.47)	2.05 (.24)	1.95 (.15)	2.65 (.95)	2.18 (.37)	2.07 (.24)
Fire-fighting						
Females	2.07 (.25)	1.97 (.25)	1.88 (.12)	2.35 (.33)	2.63 (.94)	2.42 (.60)
Males	1.80 (.22)	1.93 (.50)	1.87 (.27)	2.15 (.31)	2.53 (.80)	2.03 (.29)
Leather and wool						
Females	2.83 (.58)	2.02 (.32)	1.98 (.35)	2.30 (.14)	2.32 (.44)	2.20 (.30)
Males	2.00 (.32)	1.85 (.39)	1.83 (.35)	2.07 (.41)	1.83 (.36)	2.02 (.19)
Vinyl						
Females	1.93 (.33)	2.07 (.08)	2.03 (.33)	2.63 (1.01)	2.67 (.91)	2.13 (.33)
Males	1.82 (.28)	1.88 (.24)	1.83 (.27)	2.28 (.26)	2.27 (.39)	2.20 (.48)

Table 9

Mean Bare-Hand Errors-per-Opportunity Scores and Standard Deviations for Each Glove Assembly and Toggle Switch Spacing

Glove assembly	Front Panel Compressed	Front Panel Standard	Front Panel Expanded	Back Panel Compressed	Back Panel Standard	Back Panel Expanded
Butyl and cotton						
Females	.04(.07)	.09(.09)	.05(.04)	.10(.06)	.08(.07)	.11(.11)
Males	.13(.16)	.14(.09)	.07(.07)	.20(.15)	.10(.08)	.16(.25)
Butyl and nomex						
Females	.07(.11)	.07(.06)	.05(.04)	.19(.28)	.31(.26)	.18(.20)
Males	.07(.07)	.05(.04)	.00(.00)	.28(.38)	.22(.20)	.09(.08)
Fire-fighting						
Females	.06(.05)	.10(.09)	.07(.05)	.11(.07)	.22(.28)	.17(.21)
Males	.09(.05)	.21(.08)	.04(.07)	.09(.03)	.15(.12)	.01(.03)
Leather and wool						
Females	.08(.17)	.14(.09)	.03(.04)	.08(.07)	.07(.13)	.08(.11)
Males	.09(.05)	.06(.04)	.12(.13)	.07(.08)	.06(.03)	.03(.04)
Vinyl						
Females	.03(.04)	.05(.04)	.02(.05)	.10(.08)	.22(.23)	.10(.07)
Males	.09(.06)	.07(.07)	.04(.04)	.12(.11)	.09(.08)	.08(.08)

Table 10

Mean Bare-Handed Mean Time-of-Errors Scores and Standard Deviations (in seconds) for Each Glove Assembly and Toggle Switch Spacing

Glove assembly	Front Panel			Back Panel		
	Compressed	Standard	Expanded	Compressed	Standard	Expanded
Butyl and cotton						
Females	.70	2.52	1.53	2.00	2.05	1.88
	(1.09)	(1.33)	(1.22)	(1.11)	(1.08)	(1.52)
Males	1.70	2.65	1.40	2.35	2.57	2.57
	(1.40)	(.67)	(1.10)	(1.18)	(1.47)	(1.41)
Butyl and nomex						
Females	.85	1.65	1.78	2.33	2.65	2.50
	(1.32)	(.88)	(1.45)	(1.84)	(1.40)	(1.26)
Males	1.52	1.50	.00	2.38	2.70	1.60
	(1.21)	(1.19)	(.00)	(1.93)	(.46)	(1.28)
Fire-fighting						
Females	1.65	1.77	1.73	2.20	1.95	2.00
	(1.40)	(1.40)	(.87)	(1.12)	(1.66)	(1.64)
Males	1.78	2.53	.77	2.28	2.88	.40
	(.97)	(.45)	(1.21)	(.38)	(1.56)	(.98)
Leather and wool						
Females	1.08	2.75	1.27	2.13	.93	1.20
	(1.69)	(.65)	(1.50)	(1.11)	(1.55)	(1.35)
Males	2.40	2.08	1.98	1.20	1.77	.98
	(1.42)	(1.43)	(1.16)	(1.45)	(.90)	(1.09)
Vinyl						
Females	.03	.05	.02	.10	.22	.10
	(.04)	(.04)	(.05)	(.08)	(.23)	(.07)
Males	.09	.07	.04	.12	.09	.08
	(.06)	(.07)	(.04)	(.11)	(.08)	(.08)

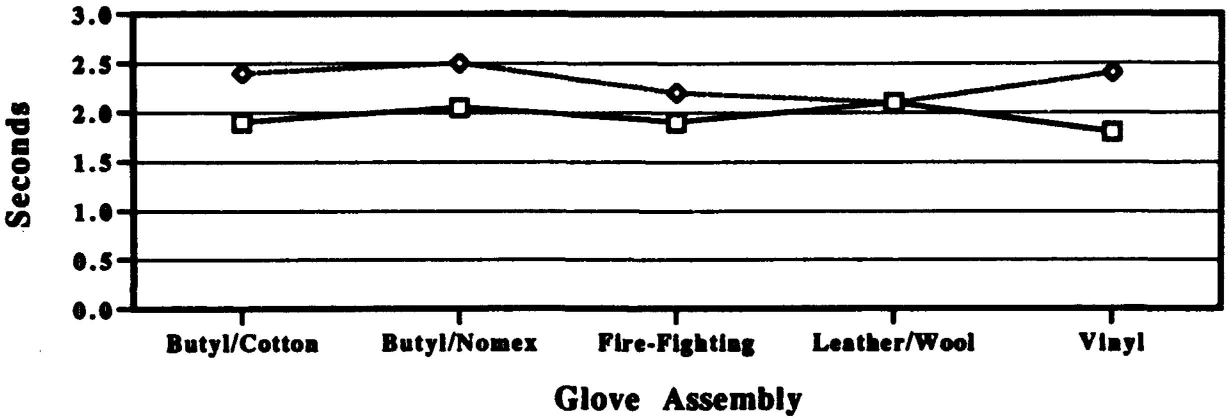


Figure 1. Glove assembly by panel location: Bare-handed best time scores, compressed toggle switch spacing.

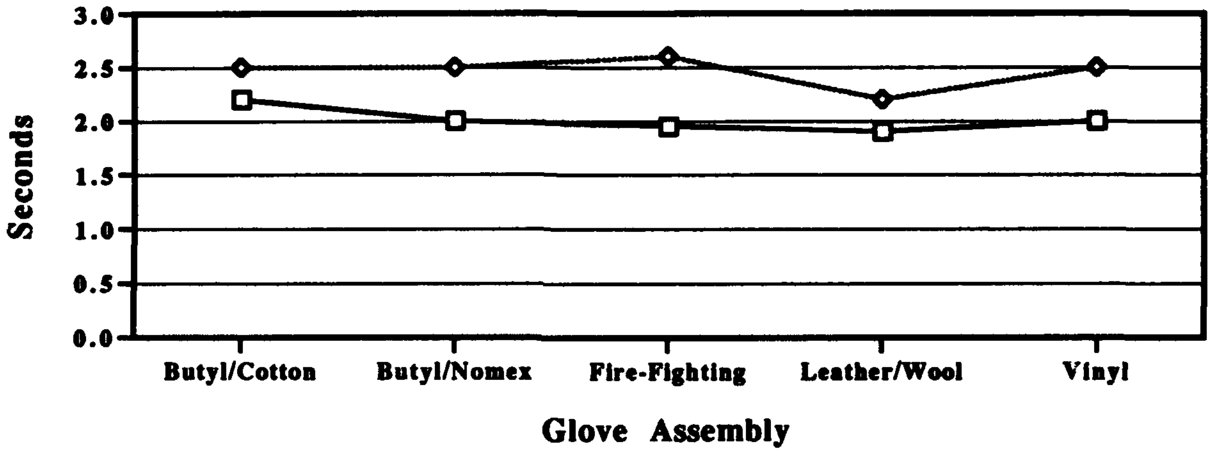


Figure 2. Glove assembly group by panel location: Bare-handed best time scores, standard toggle switch spacing.

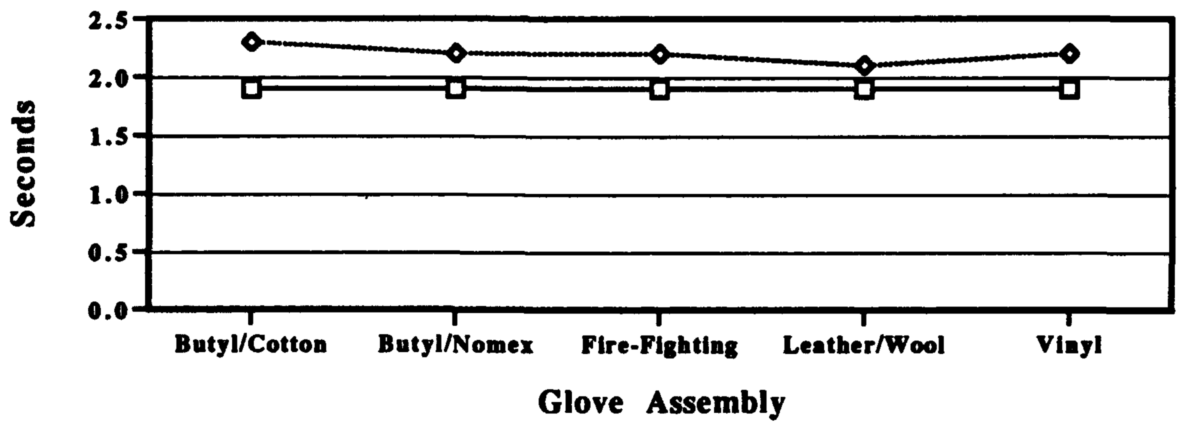


Figure 3. Glove assembly group by panel location: Bare-handed best time scores, expanded toggle switch spacing.

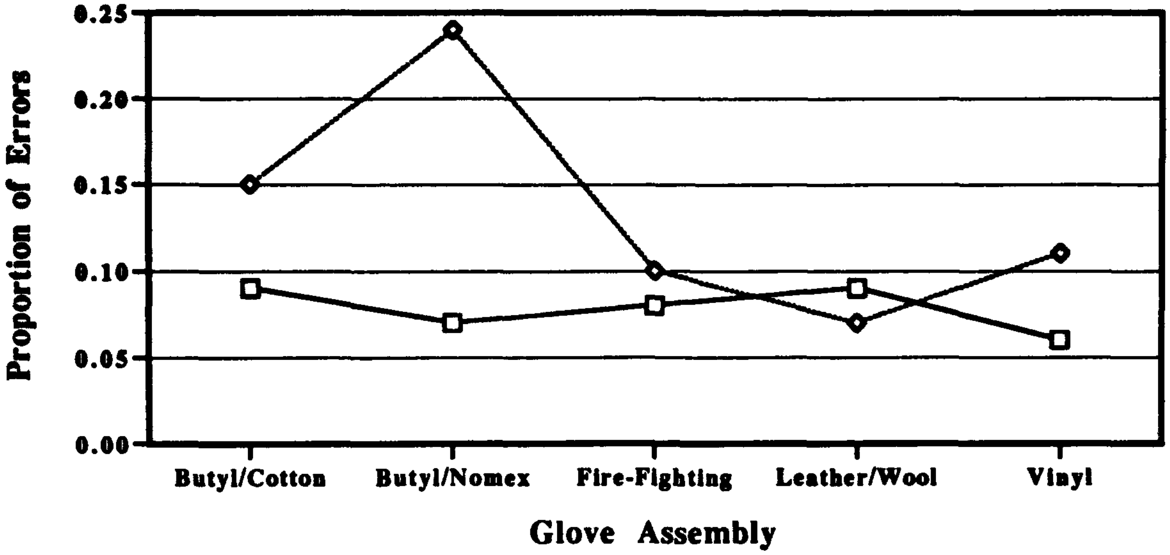
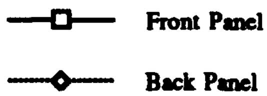


Figure 4. Glove assembly group by panel location: Bare-handed errors-per-opportunity scores, compressed toggle switch spacing.



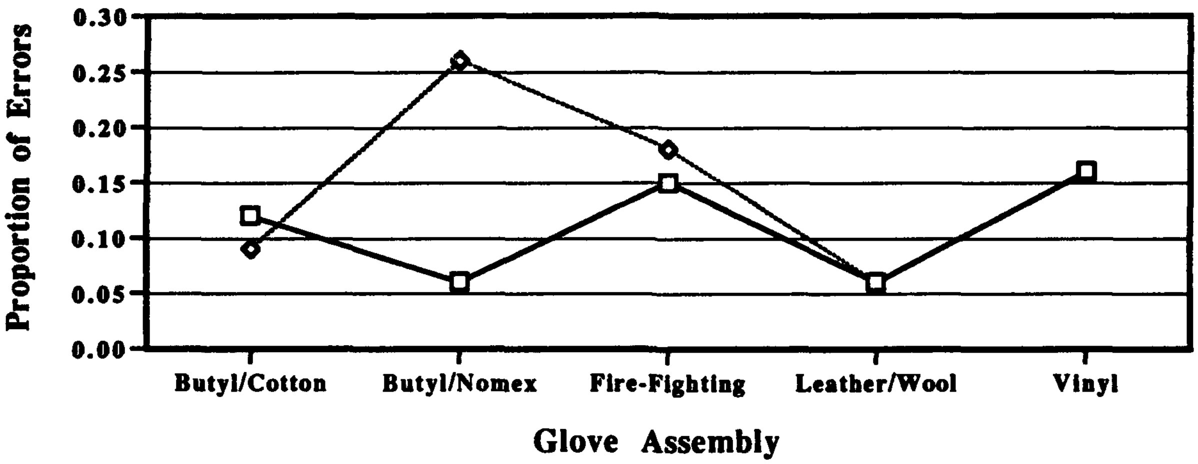
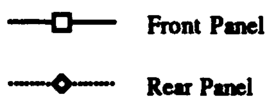


Figure 5. Glove assembly group by panel location: Bare-handed errors-per-opportunity scores, standard toggle switch spacing.



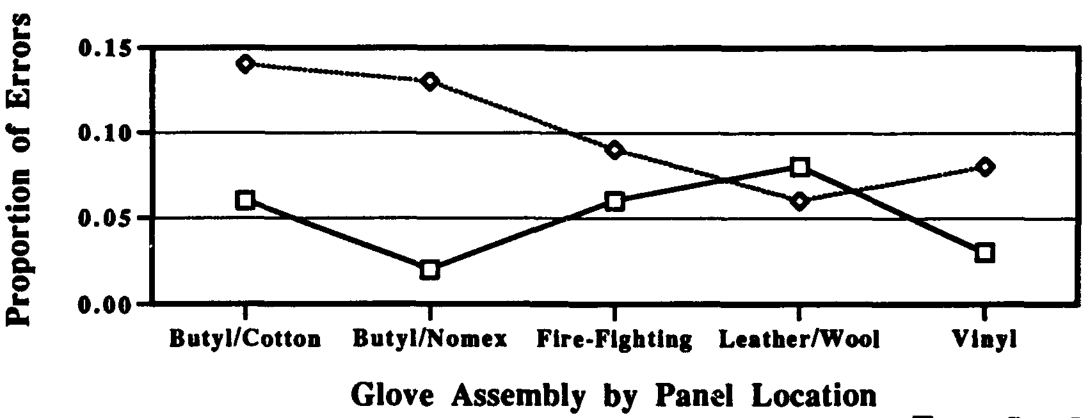
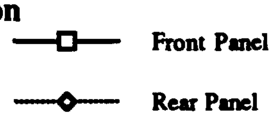


Figure 6: Glove assembly group by panel location: Bare-handed errors-per-opportunity scores, expanded toggle switch spacing.



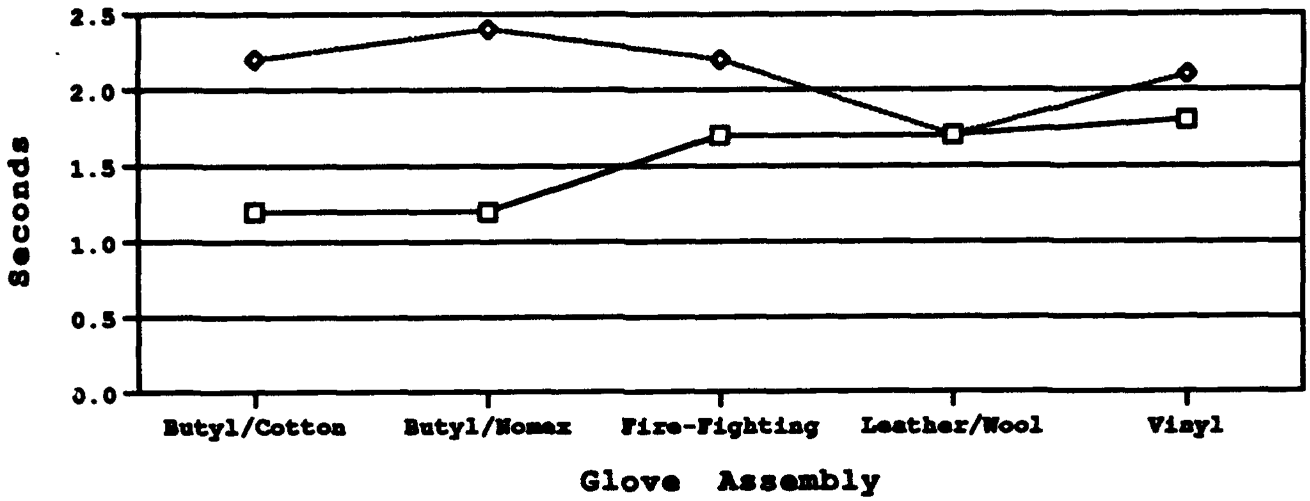


Figure 7. Glove assembly group by panel location: Bare-handed mean time-of-errors scores, compressed toggle switch spacing.

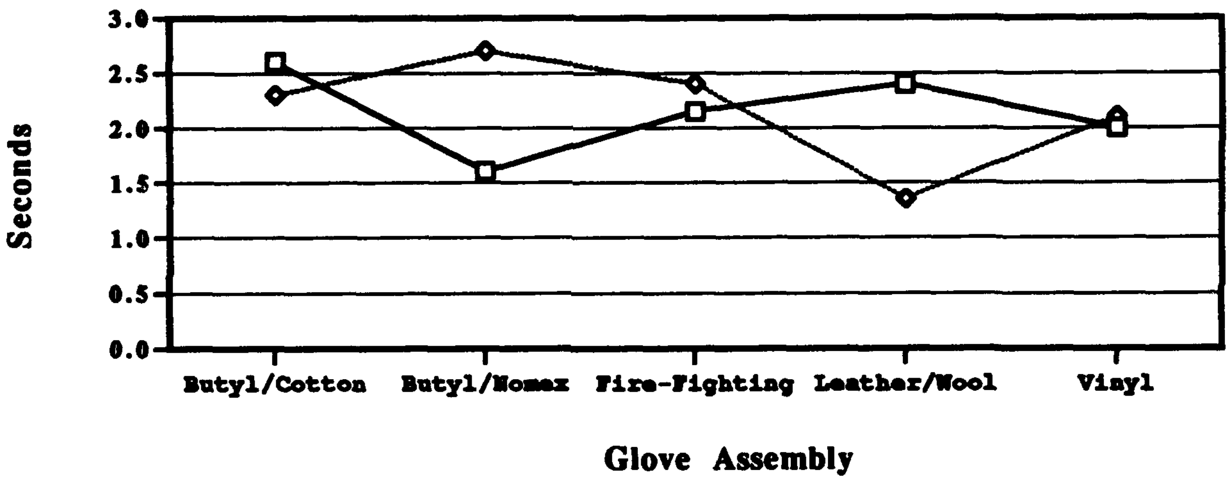


Figure 8. Group assembly by panel location: Bare-handed best time scores, standard toggle switch spacing.

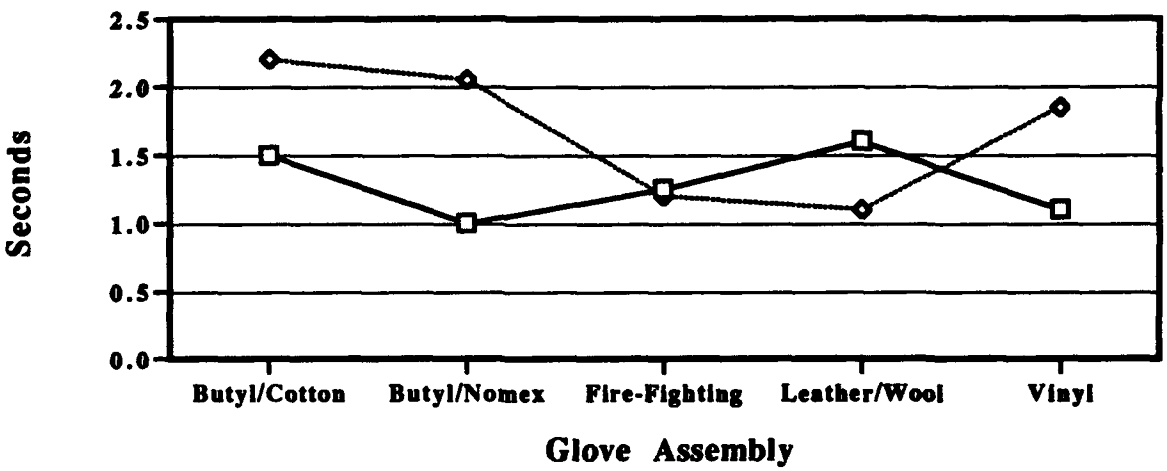


Figure 9. Group assembly by panel location: Bare-handed best time scores, expanded toggle switch spacing.

A posteriori tests to determine the source of effects could not be performed as there were no specific procedures available for doubly multivariate designs. Consequently, a post hoc doubly multivariate ANOVA of each pair combination of toggle switch spacing data was performed (i.e., compressed spacing versus standard spacing, compressed spacing versus expanded spacing, and standard spacing versus expanded spacing) to determine the source of the switch spacing effect. Additionally, repeated measures ANOVAs of each pair combination of switch spacing for each dependent variable were conducted to determine the source of other main effects. The obvious limitation of these strategies is the increased likelihood of making a Type I error. However, only those main effects that were found to be significant when the dependent variables were analyzed together were examined a posteriori. Thus, the probability of making this type of error was somewhat reduced.

The post hoc doubly multivariate ANOVAs generated significant main effects for toggle switch spacing when the compressed and expanded spacing data were compared: ($F_{(3,98)} = 3.85$, $p < .01$) and when the standard and expanded spacing data were compared: ($F_{(3,98)} = 9.24$, $p < .0001$) but not when the compressed and standard spacing data were compared. Repeated measures ANOVAs showed that the mean best time score for the expanded switch spacing was significantly faster than the mean best time score for both the compressed switch spacing ($F_{(1,100)} = 9.97, p < .002$) and the standard switch spacing ($F_{(1,100)} = 7.71$, $p < .006$). Further, the results indicated that the errors-per-opportunity scores for the expanded switch spacing were significantly less than the errors-per-opportunity scores for either the compressed ($F_{(1,100)} = 4.81$, $p < .03$) or the standard ($F_{(1,100)} = 10.46$, $p < .002$) switch spacings. Likewise, the mean time of errors was significantly faster for the expanded switch spacing than for the compressed ($F_{(1,100)} = 4.14$, $p < .04$) and the standard ($F_{(1,100)} = 17.18$, $p < .0001$) switch spacings. There were no significant differences found between the scores for the compressed switch spacing and the standard switch spacing (see Table 11).

Post hoc repeated measures ANOVAs were also conducted to identify the source of the significant panel-location effect. Univariate analyses revealed that the best time scores for the back panel were significantly slower than the best time scores for the front panel for all three switch spacings: Compressed spacing ($F_{(1,100)} = 17.92$, $p < .001$), standard spacing ($F_{(1,100)} = 14.67$, $p < .0002$), and expanded spacing ($F_{(1,100)} = 19.93$, $p < .0001$). Univariate analyses also showed that errors-per-opportunity scores for the back panel were significantly greater than the errors-per-opportunity scores for the front panel for the compressed spacing ($F_{(1,100)} = 5.59$, $p < .02$), Standard spacing ($F_{(1,100)} = 4.80$, $p < .03$), Expanded spacing ($F_{(1,100)} = 6.87$, $p < .01$). The mean time of errors was only significantly slower for the back panel compared to the front panel when the switch spacing was compressed ($F_{(1,100)} = 5.68$, $p < .02$) (see Table 12).

Gloved-Hand Data Analysis

The gloved-hand data were analyzed both with and without the two outliers in the butyl and nomex group; however, the results were not significantly different when the outliers were removed. Inspection of the data revealed that the performance of these two subjects improved during the gloved-hand condition. The female subject's errors-per-opportunity scores were 1.00 for the compressed spacing, 0.00 for the standard spacing, and 0.17

Table 11

Mean Bare-Handed Scores for the Compressed, Standard, and Expanded Toggle Switch Spacing

Dependent measures	Switch Spacing Compressed	Standard	[a]Expanded
Best time score (s)	2.19	2.21	2.05
Errors-per-opportunity score	.11	.12	.07
Mean time-of-errors score (s)	1.82	.07	1.47

[a]Scores significantly different from scores for other switch spacing.

Table 12

Mean Bare-Handed Scores for Front and Back Panel

Toggle switch spacing	Front panel	Back panel
Best time score (s)		
[a]Compressed	2.00	2.38
[a]Standard	2.01	2.42
[a]Expanded	1.90	2.21
Errors-per-opportunity score		
[a]Compressed	.08	.14
[a]Standard	.10	.15
[a]Expanded	.05	.10
Mean time-of-errors score (s)		
[a]Compressed	1.53	2.11
Standard	2.14	2.17
Expanded	1.27	1.68

[a]Front and back panel scores are significantly different.

for the expanded spacing. The mean errors-per-opportunity scores for the female butyl and nomex group for the three respective switch spacings were 0.53, 0.35, and 0.27. The male subject's errors-per-opportunity scores were 0.44 (compressed), 0.22 (standard), and 0.09 (expanded). The means for the male butyl and nomex group were 0.28 (compressed), 0.22 (standard), and 0.09 (expanded). These two subjects were included in the final data analysis.

A 5 (glove assembly) by 3 (toggle switch spacing) by 2 (panel location) by 2 (gender) doubly multivariate ANOVA was used to analyze the gloved-hand data using Wilks' Lambda criterion of statistical significance. The mean scores for all groups are shown in Table 13 (best time scores), Table 14 (errors-per-opportunity scores), and Table 15 (mean time-of-error scores).

Main effects for switch spacing, panel location, glove assembly, and gender were all significant as shown in Table 16. Significant interactions included Panel Location by Gender ($F_{(3,98)} = 3.28$, $p < .02$) as shown in Figures 10, 11, and 12 and panel location by toggle switch spacing ($F_{(6,95)} = 4.86$, $p < .0002$) as shown in Figures 13, 14, and 15.

Post hoc analysis of switch spacing main effects was performed by conducting a doubly multivariate ANOVA of each pair combination of toggle switch spacing. Analysis of the compressed and expanded spacing data found significant main effects for toggle switch spacing ($F_{(3,98)} = 12.63$, $p < .0001$). Analysis of standard and expanded spacing data also found significant main effects for toggle switch spacing ($F_{(4,97)} = 119.21$, $p < .0001$). Significant main effects for toggle switch spacing were not found when the compressed and standard spacing data were analyzed. A repeated measures ANOVA of each dependent variable for these two pairs of toggle switch spacings was performed to identify the source of significant effects. The results showed that the expanded switch spacing had a significantly faster mean best time score than either the compressed spacing ($F_{(1,100)} = 17.78$, $p < .0001$) or standard spacing ($F_{(1,100)} = 7.04$, $p < .009$). Similarly, the mean errors-per-opportunity score for the expanded spacing was significantly lower than the scores for both the compressed spacing ($F_{(1,100)} = 37.44$, $p < .0001$) and the standard spacing ($F_{(1,100)}$ 17.56, $p < .0001$). Additionally, the mean time-of-errors score was significantly faster for the expanded spacing than for the compressed spacing ($F_{(1,100)} = 16.68$, $p < .0001$) and the standard spacing ($F_{(1,100)} = 10.10$, $p < .002$) (see Table 17).

Post hoc repeated measures ANOVAs of the pair combinations of toggle switch spacing for each dependent variable were used to identify the sources of the other significant main effects. Univariate analyses showed that the best time scores for the back panel location were significantly slower than the best time scores for the front panel location for all three switch spacings: Compressed ($F_{(1,100)} = 39.44$, $p < .0001$), standard ($F_{(1,100)} = 22.40$, $p < .0001$), expanded ($F_{(1,100)} = 22.27$, $p < .0001$). Additionally, the back panel had significantly more errors per opportunity than the front panel for compressed spacing ($F_{(1,100)} = 46.63$, $p < .0001$), standard spacing ($F_{(1,100)} = 6.000$, $p < .02$), and expanded spacing ($F_{(1,100)} = 9.18$, $p < .003$). Also, the mean time-of-errors score was slower for the back panel compared to the front panel for the compressed switch spacing ($F_{(1,100)} = 30.22$, $p < .0001$) and the expanded spacing ($F_{(1,100)} = 10.15$, $p < .02$) but not for the standard switch spacing (see Table 18).

Table 13

Mean Gloved-Hand Best Time Scores and Standard Deviations
(in seconds) for Each Glove Assembly and Toggle Switch Spacing

Glove Assembly	Front Panel			Back Panel		
	Compressed	Standard	Expanded	Compressed	Standard	Expanded
Butyl and cotton						
Females	2.07	2.15	2.18	2.52	2.27	2.20
	(.42)	(.40)	(.39)	(.41)	(.45)	(.45)
Males	1.90	1.90	1.85	2.97	2.77	2.63
	(.36)	(.24)	(.33)	(.64)	(.96)	(.55)
Butyl and nomex						
Females	2.13	2.10	2.03	3.53	3.30	2.75
	(.45)	(.24)	(.30)	(1.12)	(.87)	(.93)
Males	2.12	2.18	1.87	2.75	2.28	2.15
	(.20)	(.29)	(.28)	(.91)	(.21)	(.26)
Fire-fighting						
Females	2.13	2.22	2.27	3.03	3.37	3.07
	(.32)	(.31)	(.34)	(.89)	(.70)	(.96)
Males	2.68	2.07	1.97	2.63	2.45	2.17
	(.47)	(.22)	(.34)	(.43)	(.39)	(.27)
Leather and wool						
Females	2.18	2.15	2.08	2.72	2.63	2.20
	(.35)	(.33)	(.33)	(.29)	(1.00)	(.34)
Males	2.06	2.37	1.97	2.68	2.00	1.93
	(.37)	(.96)	(.54)	(.74)	(.28)	(.23)
Vinyl						
Females	1.98	2.08	1.97	2.33	2.42	2.28
	(.53)	(.41)	(.34)	(.33)	(.40)	(.50)
Males	1.80	1.77	1.70	2.30	2.47	2.43
	(.14)	(.15)	(.18)	(.64)	(1.04)	(.33)

Table 14

Mean Gloved-Hand Errors-per-Opportunity Scores and Standard Deviations for Each Glove Assembly and Toggle Switch Spacing

	Front Panel			Back Panel		
Glove assembly	Compressed	Standard	Expanded	Compressed	Standard	Expanded
Butyl and cotton						
Females	.07 (.07)	.24 (.22)	.05 (.07)	.20 (.12)	.12 (.13)	.12 (.10)
Males	.12 (.09)	.14 (.13)	.09 (.11)	.24 (.19)	.20 (.17)	.15 (.12)
Butyl and nomex						
Females	.06 (.06))	.11 (.11)	.10 (.07)	.53 (.34)	.35 (.27)	.27 (.23)
Males	.01 (.03)	.11 (.04)	.07 (.04)	.42 (.31)	.17 (.12)	.08 (.06)
Fire-fighting						
Females	.08 (.06)	.10 (.11)	.10 (.09)	.33 (.26)	.44 (.32)	.14 (.15)
Males	.22 (.26)	.14 (.06)	.06 (.04)	.29 (.09)	.14 (.11)	.05 (.06)
Leather and wool						
Females	.14 (.08)	.12 (.11)	.03 (.05)	.31 (.12)	.20 (.31)	.11 (.07)
Males	.13 (.09)	.17 (.15)	.11 (.11)	.29 (.21)	.07 (.04)	.07 (.08)
Vinyl						
Females	.05 (.05)	.06 (.07)	.02 (.05)	.15 (.06)	.14 (.18)	.09 (.17)
Males	.05 (.05)	.07 (.06)	.03 (.03)	.19 (.12)	.17 (.09)	.15 (.11)

Table 15

Mean Gloved-Hand Mean Time-of-Errors Scores and Standard Deviations (in seconds) for Each Glove Assembly and Toggle Switch Spacing

Glove assembly	Front Panel			Back Panel		
	Compressed	Standard	Expanded	Compressed	Standard	Expanded
Butyl and cotton						
Females	1.83	2.95	1.12	2.67	1.20	2.00
	(1.46)	(.78)	(1.25)	(.52)	(1.36)	(1.22)
Males	2.35	1.83	1.47	2.75	2.80	2.30
	(1.51)	(.93)	(1.21)	(1.40)	(1.55)	(1.21)
Butyl and nomex						
Females	2.05	1.80	2.32	3.52	2.83	2.88
	(1.62)	(1.43)	(1.32)	(.77)	(1.46)	(.69)
Males	.37	2.43	2.02	2.98	2.22	2.00
	(.90)	(.48)	(1.12)	(.85)	(1.12)	(1.07)
Fire-fighting						
Females	2.52	1.93	1.88	2.80	3.60	3.10
	(1.26)	(1.54)	(1.57)	(1.50)	(.55)	(1.82)
Males	1.87	2.57	1.88	3.30	2.43	1.58
	(1.53)	(.55)	(1.29)	(.38)	(1.27)	(1.80)
Leather and wool						
Females	2.08	2.20	.77	3.00	1.55	2.83
	(1.13)	(1.14)	(1.19)	(.46)	(1.79)	(1.34)
Males	2.00	2.18	1.57	3.08	2.23	1.48
	(1.11)	(1.18)	(1.29)	(.58)	(1.32)	(1.33)
Vinyl						
Females	1.13	2.15	.45	2.47	1.52	.93
	(1.28)	(1.83)	(1.10)	(.67)	(1.67)	(1.47)
Males	1.73	1.38	1.28	2.58	2.90	2.07
	(1.38)	(1.10)	(1.51)	(.46)	(1.08)	(1.05)

Table 16

Gloved Data Significant Main Effects

Source	Num *df*	Den *df*	*F*	*p*
Gender	3	98	3.00	.03
Glove assembly	12	260	2.31	.008
Panel location	3	98	25.71	.0001
Toggle switch spacing	6	95	7.68	.0001

Univariate analyses also indicated that the type of glove worn was significant for the compressed spacing best time scores ($F_{(1,100)} = 3.63$, $p < .008$) and errors-per-opportunity score ($F_{(1,100)} = 3.19$, $p < .02$) but not for mean time-of-errors score. Glove type was not significant using the standard switch spacing but was significant for the expanded spacing for mean time-of-errors score only ($F_{(1,100)} = 2.77$, $p < .02$). Tukey's honestly significant difference (HSD) test was used to determine the source of the glove effect for the compressed and expanded spacings. The results showed that the vinyl glove produced significantly faster mean best time scores than the butyl and nomex and fire-fighting glove assemblies. The best time scores for the butyl and nomex and fire-fighting glove assemblies did not differ from each other or from the other glove assemblies. The vinyl glove score also did not differ from the score of the other glove assemblies as shown in Table 19. The mean errors-per-opportunity score for the compressed switch spacing was also significantly higher for the butyl and nomex glove assembly than for the vinyl glove. These two glove assemblies did not differ from the other glove assemblies, which did not differ from each other (see Table 20). Tukey's HSD test further determined that the mean time-of-errors score for the vinyl glove was significantly faster than the mean time-of-errors score for the butyl and nomex glove assembly. Again, these two glove assemblies did not differ from the other glove assemblies, which did not differ from each other (as shown in Table 21).

Post hoc analysis of the significant gender effect revealed that the mean best time score for male subjects was significantly faster than the mean best time score for female subjects for the standard spacing ($F_{(1,100)} = 5.38$, $p < .02$) and expanded spacing ($F_{(1,100)} = 8.06$, $p < .005$). No other significant gender differences were found (see Table 22).

Gloved Data Analysis

Difference scores, obtained by subtracting bare-handed scores from gloved scores, were analyzed to determine if the differences between gloved and bare-handed performance were significantly affected by glove type, gender, panel location, or toggle switch spacing. A 5 (glove assembly) by 3 (toggle switch spacing) by 2 (panel location) by 2 (gender) doubly multivariate analysis was used to analyze these data using Wilks' Lambda criterion of statistical significance.

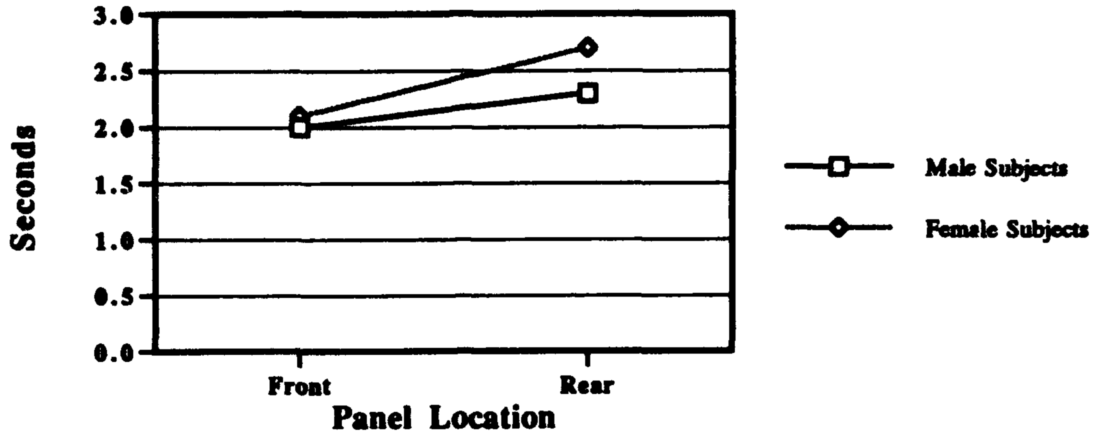


Figure 10. Panel location by gender: Gloved-hand best time scores.

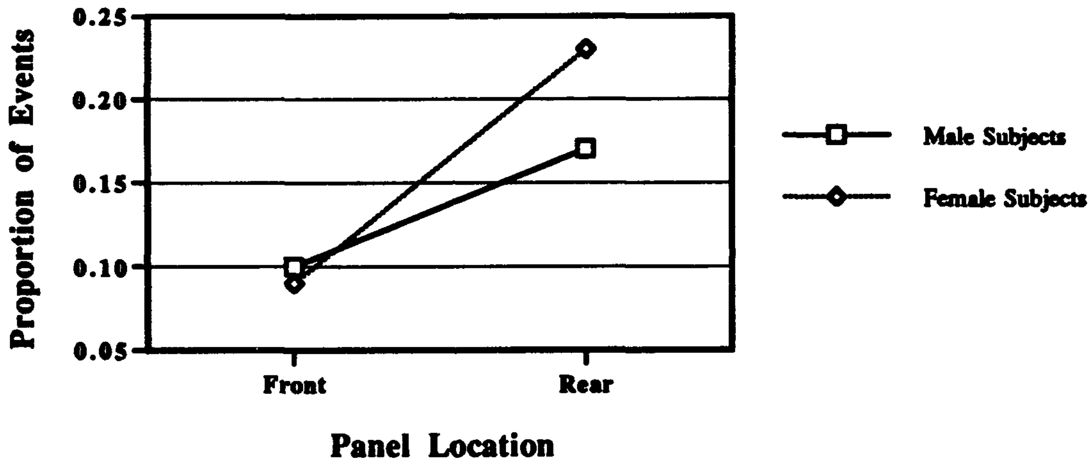


Figure 11. Panel location by gender: Glove-hand errors-per-opportunity scores.

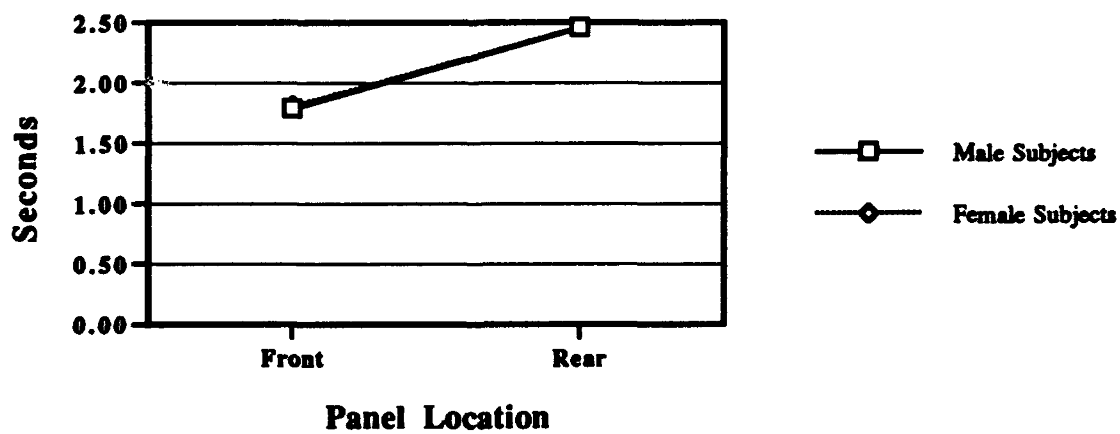


Figure 12. Panel location by gender: Gloved-hand mean time-of-errors scores.

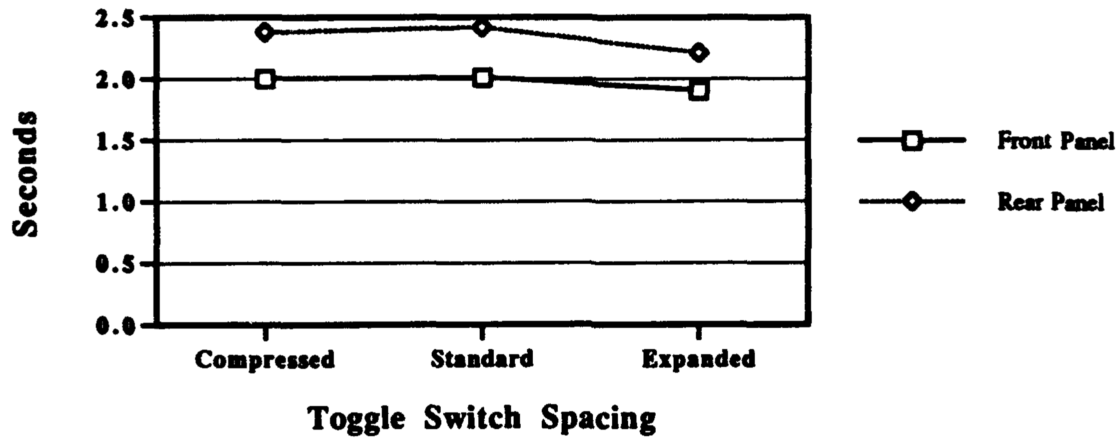


Figure 13. Panel location by toggle switch spacing:
Gloved-hand best time scores.

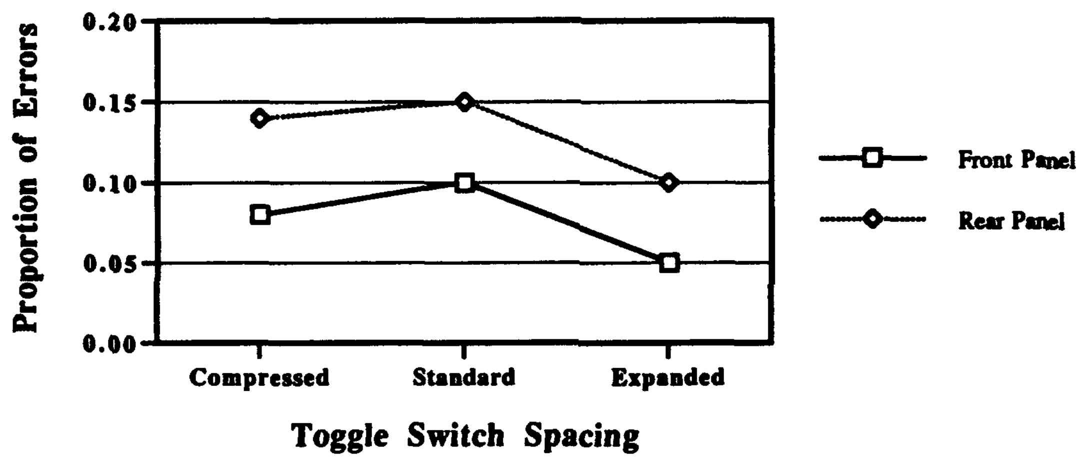


Figure 14. Panel location by toggle switch spacing:
Gloved-hand errors-per-opportunity scores.

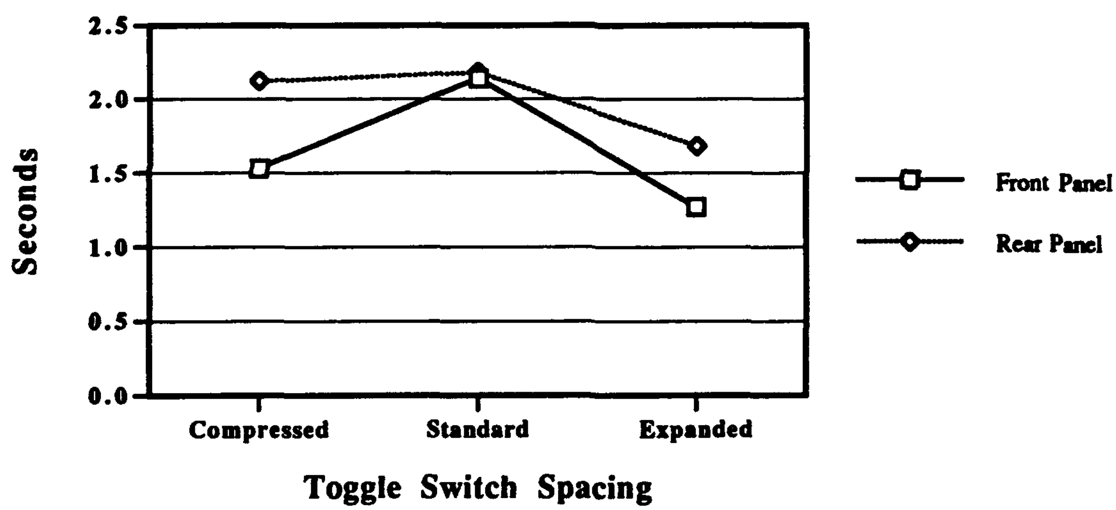


Figure 15. Panel location by toggle switch spacing:
Gloved-hand mean time-of-errors scores.

Table 17

Mean Gloved-Hand Scores for the Compressed, Standard, and Expanded Toggle Switch Spacing

	Switch Spacing		
Dependent measures	Compressed	Standard	[a]Expanded
Best time score (s)	2.43	2.35	2.18
Errors-per-opportunity score	.19	.16	.09
Mean Time-of-errors score (s)	2.35	2.24	1.77

[a]Scores significantly different from scores for other toggle switch spacing.

Table 18

Mean Bare-Handed Scores for Front and Back Panels

Toggle switch spacing	Front panel	Back panel
Best time score (s)		
[a]Compressed	2.11	2.75
[a]Standard	2.10	2.59
[a]Expanded	1.99	2.38
Errors-per-opportunity score		
[a]Compressed	.09	.30
[a]Standard	.13	.20
[a]Expanded	.07	.12
Mean time-of-errors score (s)		
[a]Compressed	1.79	2.91
Standard	2.14	2.33
[a]Expanded	1.47	2.06

[a]Front and back panel scores are significantly different from each other.

Table 19

Tukey's HSD Test for Gloved Best Time Scores for the Compressed Panel

Tukey	Grouping	Mean	Glove assembly
	A	2.63	Butyl and nomex
	A	2.62	Fire-fighting
B	A	2.41	Leather and wool
B	A	2.36	Butyl and cotton
B		2.10	Vinyl

<u>Note</u>: Means with same Tukey group letter are not significantly different (alpha = 0.05).

Table 20

Tukey's HSD Test for Gloved Errors-per-Opportunity Scores for the Compressed Panel

Tukey	Grouping	Mean	Glove assembly
	A	.26	Butyl and nomex
B	A	.23	Fire-fighting
B	A	.22	Leather and wool
B	A	.15	Butyl and cotton
B		.11	Vinyl

<u>Note</u>: Means with same Tukey group letter are not significantly different (alpha = 0.05).

Table 21

Tukey's HSD Test for Gloved Mean Time-of-Errors Scores for the Compressed Panel

Tukey	Grouping	Mean	Glove assembly
	A	2.30	Butyl and nomex
B	A	2.11	Fire-fighting
B	A	1.71	Butyl and cotton
B	A	1.52	Leather and wool
B		1.18	Vinyl

Note: Means with same Tukey group letter are not significantly different (alpha = 0.05).

Table 22

Mean Gloved-Hand Scores for Female and Male Subjects

Toggle switch spacing	Female	Male
Best time score (s)		
Compressed	2.46	2.39
[a]Standard	2.47	2.22
[a]Expanded	2.30	2.07
Errors-per-opportunity score		
Compressed	.19	.20
Standard	.19	.14
Expanded	.10	.08
Mean time-of-errors (s)		
Compressed	2.40	2.30
Standard	2.17	2.30
Expanded	1.77	1.76

[a]Female and male scores are significantly different.

Significant main effects included glove assembly ($F_{(12,260)} = 2/14$. $p < .01$), panel location ($F_{(3,98)} = 3.28$, $p < .02$), and switch spacing ($F_{(6,95)} = 2.68$, $p < .02$). Main effects for gender were not significant. The only significant interaction was Panel Location x Toggle Switch Spacing ($F_{(6,95)} = 2.37$, $p < .04$) as shown in Figures 16, 17, and 18.

Post hoc analysis of the toggle switch spacing effect was conducted by performing a doubly multivariate ANOVA on each pair combination of toggle switch spacings. Statistical comparison of the compressed and expanded spacing data revealed significant main effects for switch spacing ($F_{(3,98)} = 4.47$, $p < .005$). Significant main effects for switch spacing were not found when the compressed and standard spacing data and the standard and expanded spacing data were analyzed. The repeated measures ANOVAs performed on the compressed and expanded spacing data found switch spacing to be significant only for errors-per-opportunity difference scores ($F_{(1,100)} = 12.47$, $p < .0006$). The errors-per-opportunity difference score for the compressed switch spacing ($M = .09$) was significantly larger than the score for the expanded switch spacing ($M = .02$).

Repeated measures ANOVAs were used to further investigate the source of significant effects. Univariate statistical analyses showed the mean best time difference score for the back panel to be significantly larger than the mean best time difference score for the front panel, but only when the switch spacing was compressed ($F_{(1.100)} = 5.17$, $p < .02$). Also, the errors-per-opportunity difference score for the back panel was significantly higher than the errors-per-opportunity difference score for the front panel but again, only for the compressed toggle switch spacing ($F_{(1,100)} = 18.12$, $p < .0001$). No other significant differences between front and back panel difference scores were found (see Table 23).

Univariate analyses also showed glove assembly to be significant for best time difference scores for the compressed switch spacing only ($F_{(1,100)} = 3.25$, $p < .01$). No significant glove assembly effect for errors-per-opportunity difference scores or mean time-of-errors difference scores was found for any of the toggle switch spacings. Tukey's HSD test was used to analyze the best time difference scores for each glove assembly for the compressed spacing. The results showed that the difference in operation speed between the bare hand and the fire-fighting glove was significantly greater than the difference in the operating speed between the bare-handed and the vinyl glove. The best time difference scores for the other glove assemblies did not differ from the scores for the vinyl or the fire-fighting gloves or among each other (see Table 24).

Bare-Handed versus Gloved-Hand Data Analysis

To determine if overall differences between gloved and bare-handed performance existed, differences between bare-handed and gloved scores were analyzed. A 5 (glove assembly) by 3 (toggle switch spacing) by 2 (panel location) by 2 (hand condition) by 2 (gender) repeated measures ANOVA was used to analyze each of the three dependent measures using Wilks' Lambda criterion of statistical significance. The repeated measures included the three toggle switch spacings as well as hand condition, gloved or bare. Differences resulting from hand-wear condition were studied. Other conditions were

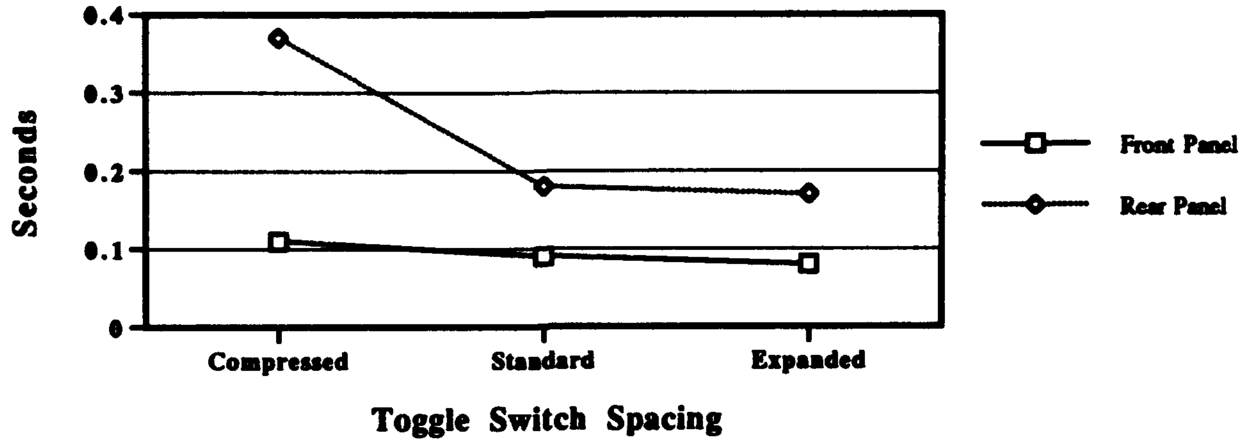


Figure 16. Panel location by toggle switch spacing: Best time difference scores.

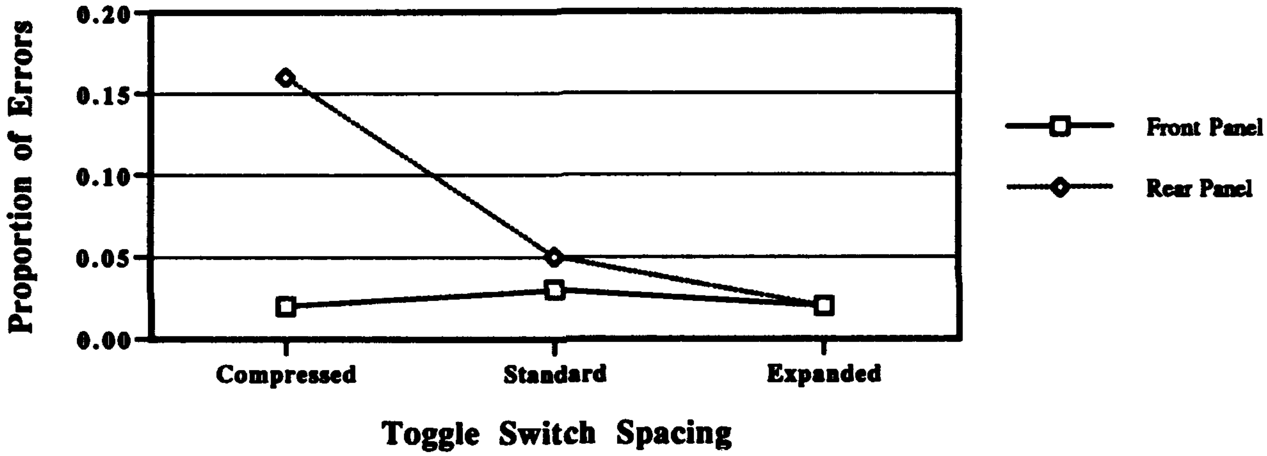


Figure 17. Panel location by toggle switch spacing: Errors-per-opportunity difference scores.

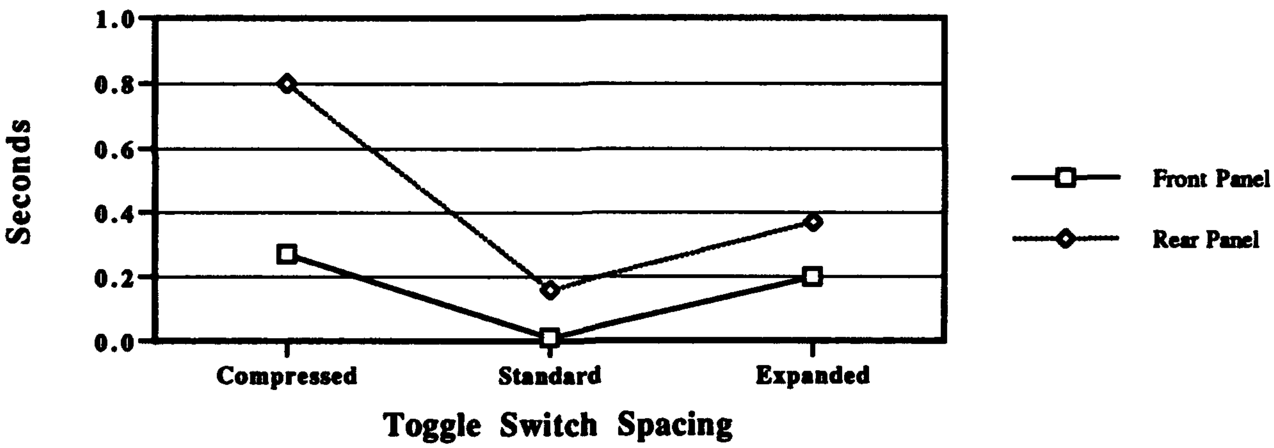


Figure 18. Panel location by toggle switch spacing: Mean time-of-errors difference scores.

Table 23

Mean Difference Scores for Front and Back Panels

Toggle switch spacing	Front panel	Back panel
Best time score (s)		
[a]Compressed	.11	.37
Standard	.09	.18
Expanded	.08	.17
Errors-per-opportunity score		
[a]Compressed	.02	.16
Standard	.03	.05
Expanded	.02	.02
Mean time-of-errors score (s)		
Compressed	.26	.80
Standard	.01	.16
Expanded	.21	.37

[a]Front and back panel scores are significantly different.

Table 24

Tukey's HSD Test for Best Time Difference Scores (in seconds) for the Compressed Panel

Tukey	Grouping	Mean	Glove assembly
	A	.53	Fire-fighting
B	A	.33	Butyl and nomex
B	A	.22	Leather and wool
B	A	.16	Butyl and cotton
B		-.06	Vinyl

Note. Means with same Tukey group letter are not significantly different (alpha = 0.05).

previously analyzed using a doubly multivariate ANOVA. Since a multivariate ANOVA could not be used to analyze these differences, protection against making one or more Type I errors was provided by using the Bonferroni procedure to establish the alpha level at 0.017 rather than 0.05 (Kirk, 1982). The mean gloved and bare-handed scores are shown in Table 25.

The results showed significant main effects for hand condition for best time scores ($F_{(1,100)} = 27.75$, $p < .0001$). Also, a significant hand condition by glove assembly interaction for best time scores resulted ($F_{(4,100)} = 4.46$, $p < .002$) as shown in Figure 19. No other interactions for best time score were significant. Post hoc analysis was conducted using Tukey's HSD test. The results indicated that the mean gloved best time score for the compressed switch spacing was significantly slower than the mean bare-handed best time score for the compressed, standard, and the expanded toggle switch spacings. Further, the mean gloved best time score for the standard switch spacing was significantly slower than the mean bare-handed best time scores for all three switch spacings. Additionally, the mean gloved best time score for the expanded switch spacing was significantly slower than the mean bare-handed best time score for that same spacing, but it did not differ from the mean bare-handed best time scores for the compressed and standard spacings.

The results of the errors-per-opportunity data analysis also showed significant main effects for hand condition ($F_{(1,100)} = 26.39$, $p < .0001$) as well as three significant interactions: Hand Condition x Panel Location ($F_{(4,100)} = 9.14$, $p < .003$) as shown in Figure 20, Hand Condition x Toggle Switch Spacing ($F_{(2,99)} = 6.21$, $p < .003$) as shown in Figure 21, and Hand Condition x Toggle Switch Spacing x Panel Location ($F_{(2,99)} = 6.25$, $p < .003$) as shown in Figure 22. Post hoc analysis, using Tukey's HSD test, found the mean gloved errors-per-opportunity score for the compressed and standard spacings to be significantly greater than the mean bare-handed errors-per-opportunity score for all three spacings. Further, the mean gloved errors-per-opportunity score for the expanded switch spacing was significantly less than the mean bare-handed errors-per-opportunity score for the standard spacing but did not differ from the compressed or expanded spacing bare-handed scores.

The mean time-of-errors data analysis also revealed significant main effects for hand condition ($F_{(1,100)} = 9.28$, $p < .003$). No significant interactions were found. Tukey's HSD test was used to perform the post hoc analysis. The results showed that the mean gloved mean time-of-errors scores for the compressed switch spacing was significantly slower than the mean bare-handed mean time-of-errors scores for the compressed and expanded spacings but did not differ from the mean bare-handed mean time-of-errors score for the standard switch spacing. Similarly, the mean gloved mean time-of-errors score for the standard spacing was significantly slower than the mean bare-handed scores for the compressed and expanded spacings and did not differ from the mean bare-handed score for the standard spacing. The mean gloved mean time-of-errors score for the expanded spacing was significantly faster than the mean bare-handed mean time-of-errors score for the standard spacing but did not differ from the mean bare-handed scores for the compressed and expanded switch spacings.

Table 25

Mean Gloved-Hand and Bare-Handed Scores

Toggle switch spacing	Bare-handed	Gloved hand
Best time score (s)		
[a]Compressed	2.19	2.43
[a]Standard	2.21	2.35
[a]Expanded	2.05	2.18
Errors-per-opportunity score		
[a]Compressed	.11	.19
[a]Standard	.12	.16
Expanded	.07	.09
Mean time-of-errors (s)		
[a]Compressed	1.82	2.35
Standard	2.15	2.24
Expanded	1.47	1.77

[a]Gloved-hand and bare-handed scores are significantly different.

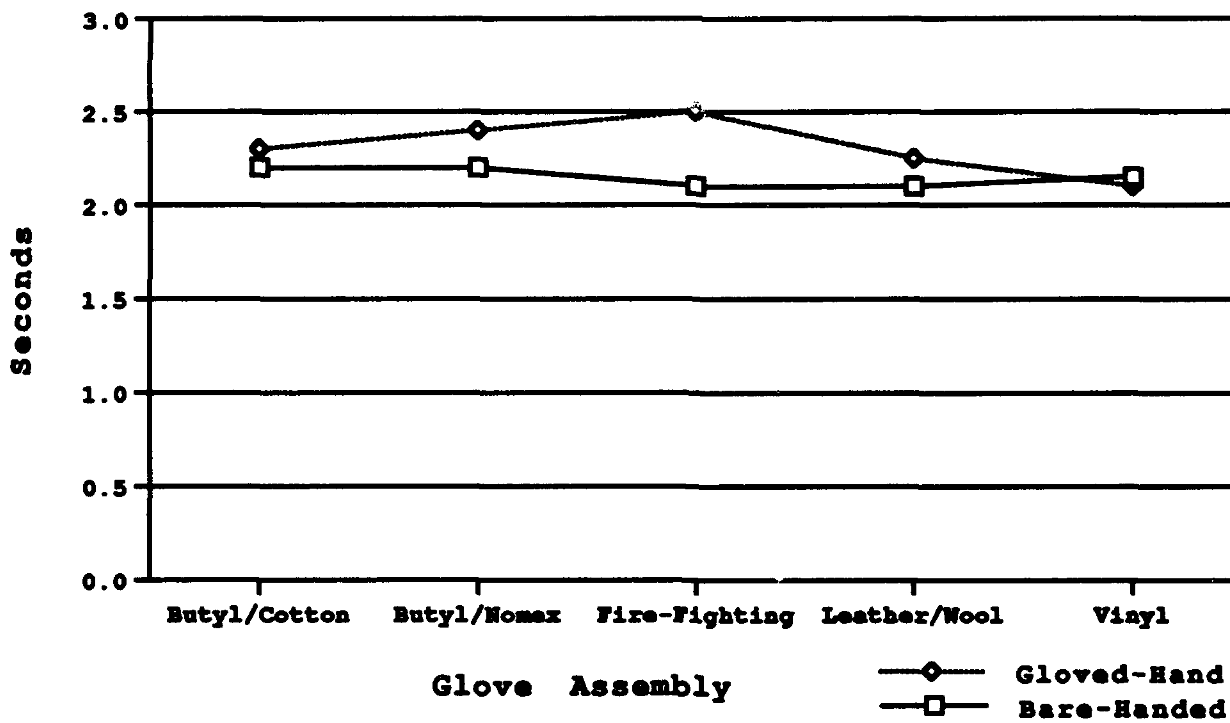


Figure 19. Hand Condition by glove assembly: Best time scores.

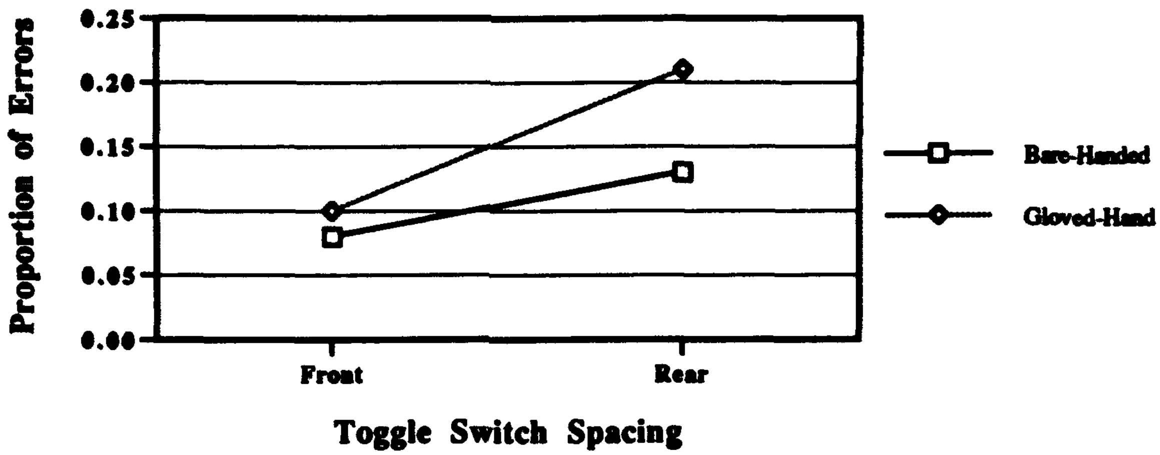


Figure 20. Hand condition by panel location: Errors-per-opportunity scores.

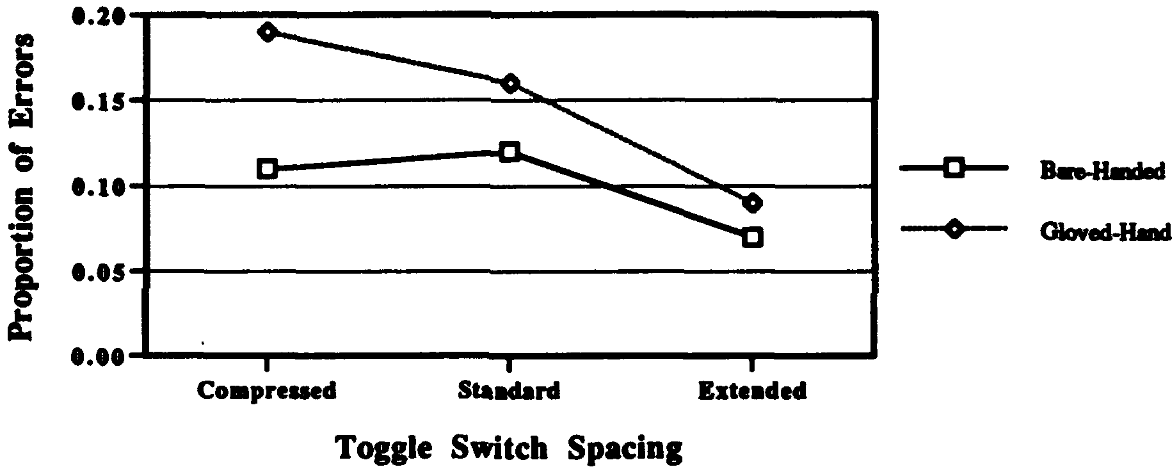


Figure 21. Hand condition by toggle switch spacing: Errors-per-opportunity score.

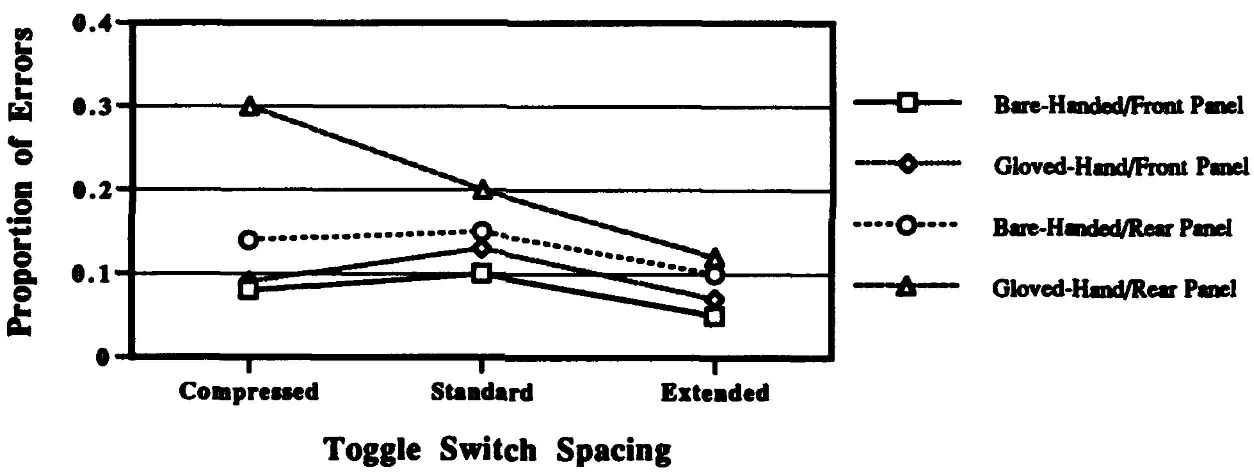


Figure 22. Hand condition by panel location and toggle switch spacing: errors-per-opportunity score.

Individual Glove Data Analysis

To determine the differential effects of individual gloves, each glove was analyzed separately. A 3 (toggle switch spacing) by 2 (gender) doubly multivariate ANOVA was performed on the data. Also, individual glove data were analyzed to determine differences between gloved and bare-handed toggle switch operation by conducting a 3 (toggle switch spacing) by 2 (hand condition) by 2 (gender) repeated measures ANOVA of each dependent measure. To protect against an inflated Type I error rate, Bonferroni's procedure was used to establish the alpha level at 0.017 rather than 0.05 for all repeated measures ANOVAs. There were 24 subjects in each glove assembly group (12 males, 12 females) with each subject performing the task gloved and bare-handed with compressed, standard, and expanded switch spacings. Wilks' Lambda was used as the criterion of statistical significance.

Analysis of the Butyl and Cotton Glove Assembly Data

Analysis of the bare-handed data found significant main effects for panel location only ($F_{(3,18)} = 4.86$, $p < .01$). Both gender and toggle switch spacing were not significant. A post hoc repeated measures ANOVA on all pair combinations of toggle switch spacing for each dependent variable was performed. Univariate analyses showed that the mean best time score for the back panel was significantly slower than the mean score for the front panel but only for the compressed switch spacing ($F_{(1,20)} = 16.36$, $p < .0006$). No other significant panel location effects were found as shown in Table 26.

Significant main effects for panel location were also found when the gloved data were analyzed ($F_{(3,18)} = 5.99$, $p < .005$). No other main effects or interactions were significant. A post hoc repeated measures ANOVA was performed on all switch-spacing combinations for each dependent variable. The univariate analyses of the compressed spacing data revealed that compared to the front panel scores, the back panel had a significantly slower best time score ($F_{(1,20)} = 15.56$, $p < .0008$) and a significantly greater errors-per-opportunity score ($F_{(1,20)} = 5.93$, $p < .02$). Univariate analyses of the standard spacing data showed that the best time score for the back panel was significantly slower than that for the front panel ($F_{(1,20)} = 4.33$, $p < .05$). Similarly, univariate analyses of the expanded switch spacing data showed that the best time score for the back panel was significantly slower than that for the front panel ($F_{(1,20)} = 5.00$, $p < .04$). No other significant panel effects were found (see Table 27).

Analysis of the difference data revealed no significant main effects or interactions. Analysis of the bare-handed versus gloved-hand data also did not reveal any significant hand condition effects or interactions as shown in Table 28.

Analysis of the Butyl and Nomex Glove Assembly Data

Analysis of the bare-handed data found significant main effects for panel location only ($F_{(3,18)} = 4.81$, $p < .01$). There was one significant interaction, Gender x Toggle Switch Spacing ($F_{(6,15)} = 3.00$, $p < .04$). As stated previously, these data contained one male and one female outlier, the analysis was repeated substituting the mean gender scores for the respective outliers rather than eliminating these scores because of the small group size.

Table 26

Butyl and Cotton Glove Assembly Data: Mean Bare-Handed Scores for Front and Back Panels

Toggle switch spacing	Front panel	Back panel
Best time score (s)		
[a]Compressed	1.93	2.47
Standard	2.20	2.46
Expanded	1.92	2.31
Errors-per-opportunity score		
Compressed	.09	.15
Standard	.12	.09
Expanded	.06	.14
Mean time-of-errors score (s)		
Compressed	1.20	2.17
Standard	2.58	2.31
Expanded	1.47	2.22

[a]Front and back panel scores are significantly different.

Table 27

Butyl and Cotton Glove Assembly Data: Mean Gloved-Hand Scores for Front and Back Panels

Toggle switch spacing	Front panel	Back panel
Best time score (s)		
[a]Compressed	1.98	2.74
[a]Standard	2.02	2.52
[a]Expanded	2.02	2.42
Errors-per-opportunity score		
[a]Compressed	.09	.22
Standard	.16	.19
Expanded	.07	.14
Mean time-of-errors score (s)		
Compressed	2.09	2.71
Standard	2.00	2.39
Expanded	1.29	2.13

[a]Front and back panel scores are significantly different.

Table 28

Butyl and Cotton Glove Assembly Data: Mean Bare-Handed and Gloved-Hand Scores

Toggle switch spacing	Bare-handed	Gloved hand
Best time score (s)		
Compressed	2.20	2.36
Standard	2.33	2.27
Expanded	2.12	2.22
Errors-per-opportunity score		
Compressed	.12	.15
Standard	.10	.17
Expanded	.10	.10
Mean time-of-errors score (s)		
Compressed	1.69	2.40
Standard	2.45	2.20
Expanded	1.85	1.71

Note. Bare-handed and gloved-hand scores are significantly different.

The results of the second analysis did not reveal any significant interactions. Repeated measures ANOVAs were performed on the data. The univariate analyses showed panel location was not significant for the compressed switch spacing. However, panel location was significant for the standard switch spacing as the back panel had a significantly slower mean best time score than the front panel ($F_{(1,20)} = 4.58$, $p < .04$), significantly more errors per opportunity than the front panel ($F_{(1,20)} = 8.68$, $p < .008$) and significantly slower mean time of errors than the front panel ($F_{(1,20)} = 6.68$, $p < .02$). A significant panel location effect also resulted for the expanded switch spacing as the following back panel scores were inferior to the front panel scores: best time ($F_{(1,20)} = 6.62$, $p < .02$), errors per opportunity ($F_{(1,20)} = 5.85$, $p < .03$), and mean time of errors ($F_{(1,20)} = 6.06$, $p < .02$) (see Table 29).

The analysis of the gloved data showed significant main effects for gender ($F_{(3,18)} = 5.93$, $p < .005$) and panel location ($F_{(3,18)} = 30.54$, $p < .0001$). Panel Location x Gender was the only significant interaction ($F_{(3,18)} = 4.06$, $p < .02$) as shown in Figures 23, 24, and 25. Post hoc repeated measures ANOVAs of the switch spacing pairs for each dependent variable were conducted to discover the source of the gender effects. Univariate analyses found gender to be significant for the compressed switch spacing as the mean time-of-errors scores for male subjects were significantly faster than the mean time-of-errors scores for female subjects ($F_{(1,20)} = 6.21$, $p < .02$). Gender was determined to be significant for the standard panel also as the best time score for male subjects was significantly faster than the best time score for female subjects ($F_{(1,20)} = 5.59$, $p < .03$). Additionally, gender was significant for the expanded switch spacing as female subjects made significantly more errors per opportunity than male subjects ($F_{(1,20)} = 4.60$, $p < .04$). No other significant gender effects resulted (see Table 30).

Table 29

Butyl and Nomex Glove Assembly Data: Mean Bare-Handed Scores for Front and Back Panels

Toggle switch spacing	Front panel	Back panel
Best time score (s)		
Compressed	2.06	2.54
[a]Standard	1.99	2.50
[a]Expanded	1.87	2.24
Errors-per-opportunity score		
Compressed	.07	.24
[a]Standard	.06	.26
[a]Expanded	.02	.13
Mean time-of-errors score (s)		
Compressed	1.57	2.67
[a]Standard	1.18	2.36
[a]Expanded	.89	2.05

[a]Front and back panel scores are significantly different.

Table 30

Butyl and Nomex Glove Assembly Data: Mean Gloved-Hand Scores for Female and Male Subjects

Toggle switch spacing	Female	Male
Best time score (s)		
Compressed	2.83	2.43
[a]Standard	2.70	2.23
Expanded	2.39	2.01
Errors-per-opportunity score		
Compressed	.30	.22
Standard	.23	.14
[a]Expanded	.18	.07
Mean time-of-errors score (s)		
[a]Compressed	2.78	1.67
Standard	2.32	2.32
Expanded	2.60	1.99

[a]Female and male scores are significantly different.

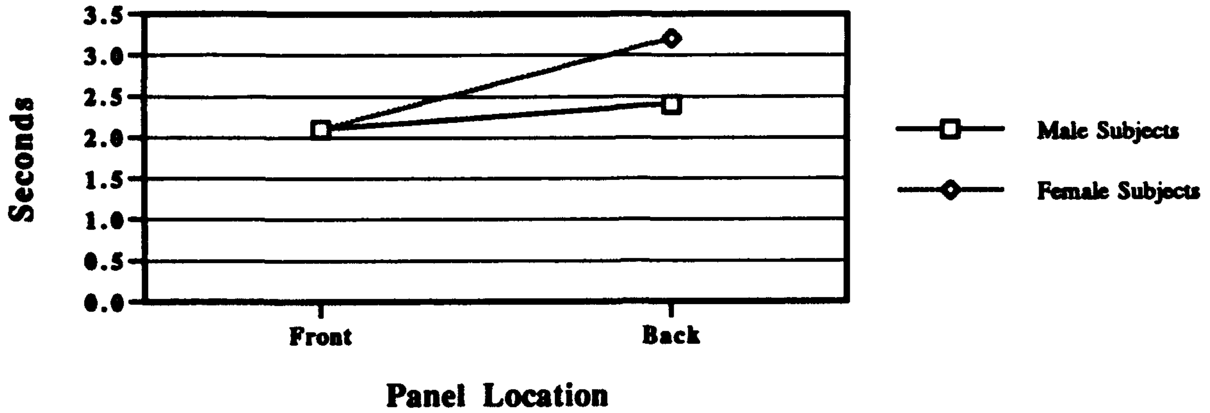


Figure 23. Panel location by gender: Butyl and nomex glove assembly, gloved-hand best time scores.

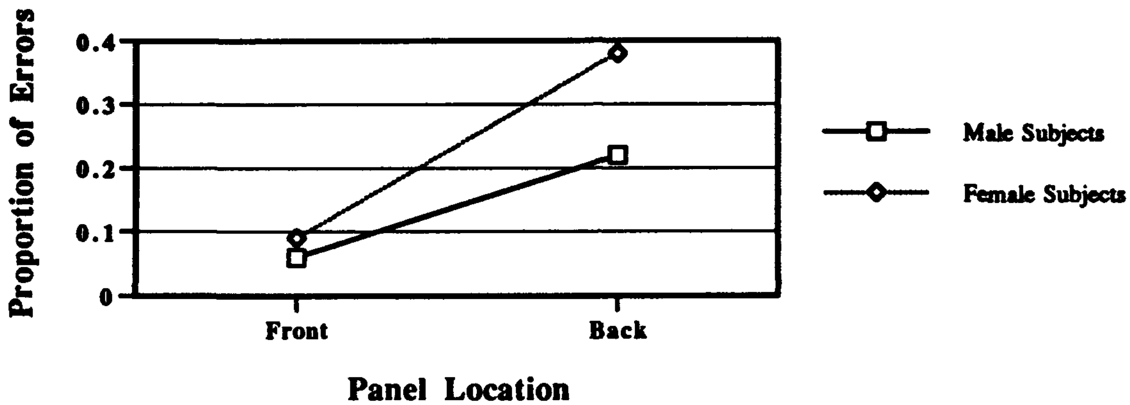


Figure 24. Panel location by gender: Butyl and nomex glove assembly, gloved-hand errors-per-oppportunity scores.

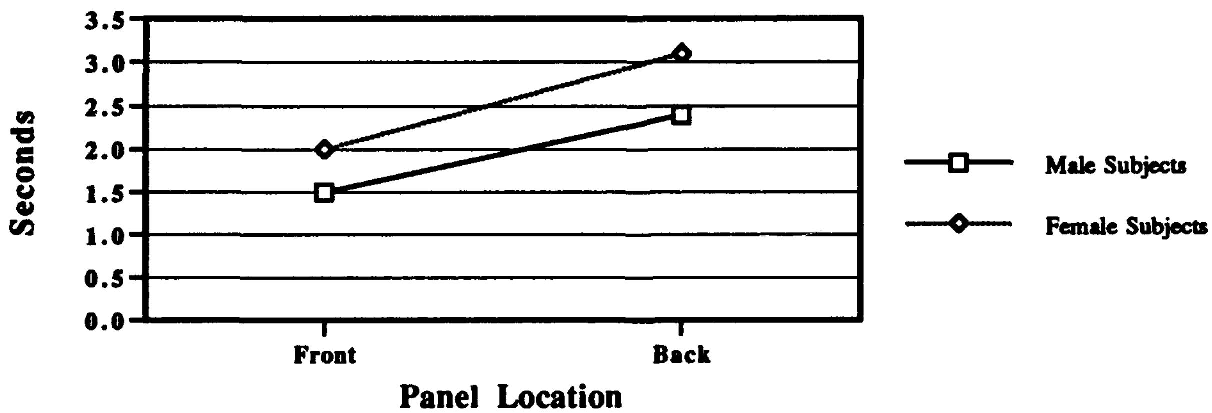


Figure 25. Panel location by gender: Butyl and nomex glove assembly, gloved-hand mean time-of-errors scores.

Further examination of the significant panel location effect was conducted using repeated measures ANOVAs. The univariate analyses of the data revealed a significant panel location effect for the compressed switch spacing as the following back panel scores were significantly inferior to the front panel scores: best time ($F_{(1,20)} = 10.63$, $p < .004$), errors per opportunity ($F_{(1,20)} = 21.03$, $p < .0002$), and mean time of errors ($F_{(1,20)} = 21.07$, $p < .0002$). Univariate analysis of the standard spacing data also showed a significant panel location effect as the back panel had significantly slower best time scores ($F_{(1,20} = 10.84$, $p < .004$) and significantly more errors per opportunity ($F_{(1,20)} = 4.86$, $p < .04$). Additionally, the mean best time score for the back panel was significantly slower than the front panel best time score for the expanded switch spacing ($F_{(1,20)} = 5.48$, $p < .04$). No other significant panel location effects were found as shown in Table 31.

Analysis of the difference data with mean scores inserted for the outlier scores showed significant main effects for panel location ($F_{(3,18)} = 52.33$, $p < .001$). No other significant main effects of interaction resulted. Post hoc analysis was conducted by performing repeated measures ANOVAs on the pair combinations of toggle switch spacing for each dependent variable. The results indicated that error-per-opportunity difference scores for the back panel were significantly greater than the front panel score when the switch spacing was compressed ($F_{(1,20)} = 26.68$, $p < .0001$) and when the switch spacing was standard ($F_{(1, 20)} = 6.57$, $p < .02$) (see Table 32).

Table 31

Butyl and Nomex Glove Assembly Data: Mean Bare-Handed and Gloved-Hand Scores

Toggle switch spacing	Bare-handed	Gloved-handed
Best time scores (s)		
[a]Compressed	2.30	2.63
Standard	2.25	2.47
Expanded	2.06	2.20
Errors-per-opportunity score		
[a]Compressed	.15	.26
[a]Standard	.16	.19
[a]Expanded	.08	.13
Mean time of errors score (s)		
Compressed	1.77	2.23
Standard	2.12	2.32
[a]Expanded	1.47	2.30

[a]Front and back panel scores are significantly different.

Table 32

Butyl and Nomex Glove Assembly Data: Mean Difference Scores for Front and Back Panels

Toggle switch spacing	Front panel	Back panel
Best time score (s)		
Compressed	.07	.60
Standard	.15	.29
Expanded	.07	.21
Errors-per-opportunity score		
[a]Compressed	-.08	.45
[a]Standard	.05	.24
Expanded	.06	.08
Mean time-of-errors score (s)		
Compressed	.02	.89
Standard	-.15	.54
Expanded	1.27	.37

[a]Front and back panel scores are significantly different.

Analysis of the bare-handed versus gloved-hand data did not show significant hand condition main effects or interactions. However, if it had not been for the conservative alpha level, significant main effects for hand condition would have been found for errors-per-opportunity analysis ($F_{(1,20)} = 4.58$, $p < .04$) and mean time-of-errors analysis ($F_{(1,20)} = 6.38$, $p < .02$). The data were analyzed again with the mean scores inserted for the bare-handed outlier scores. The results showed significant main effects for hand condition for errors-per-opportunity analysis ($F_{(1,20)} = 104.01$, $p < .0001$). Also the errors-per-opportunity data analysis revealed two significant interactions: Hand Condition x Panel Location ($F_{(1,20)} = 68.51$, $p < .0001$) as shown in Figure 26 and Hand Condition by Switch Spacing by Panel Location ($F_{(1,20)} = 6.04$, $p < .01$) as shown in Figure 27. Post hoc analysis of the errors-per-opportunity scores was performed using Tukey's HSD test. The findings showed that gloved errors-per-opportunity scores for the compressed, standard, and expanded spacings were each significantly greater than the bare-handed errors-per-opportunity score for all switch spacings.

Analysis of the bare-handed versus gloved-hand data with the mean scores substituted for the outlier scores also revealed that the main effects for hand condition were closer to being significant for the best time score data ($F_{(1,20)} = 6.42$, $p < .02$) while the findings for the mean time of errors data remained the same ($F_{(1,20)} = 6.38$, $p < .02$). Since these results were close to this study's very conservative alpha level (.017), post hoc analyses were performed on these data using Tukey's HSD test. The results indicated that the mean gloved best time score for the compressed switch spacing was significantly slower than the mean bare-handed best time scores for the compressed, standard, and expanded spacings. Additionally, the mean gloved best time score for the standard spacing was significantly slower than the mean bare-handed best time score for the expanded spacing. No other significant differences between bare-handed and gloved best time scores were found.

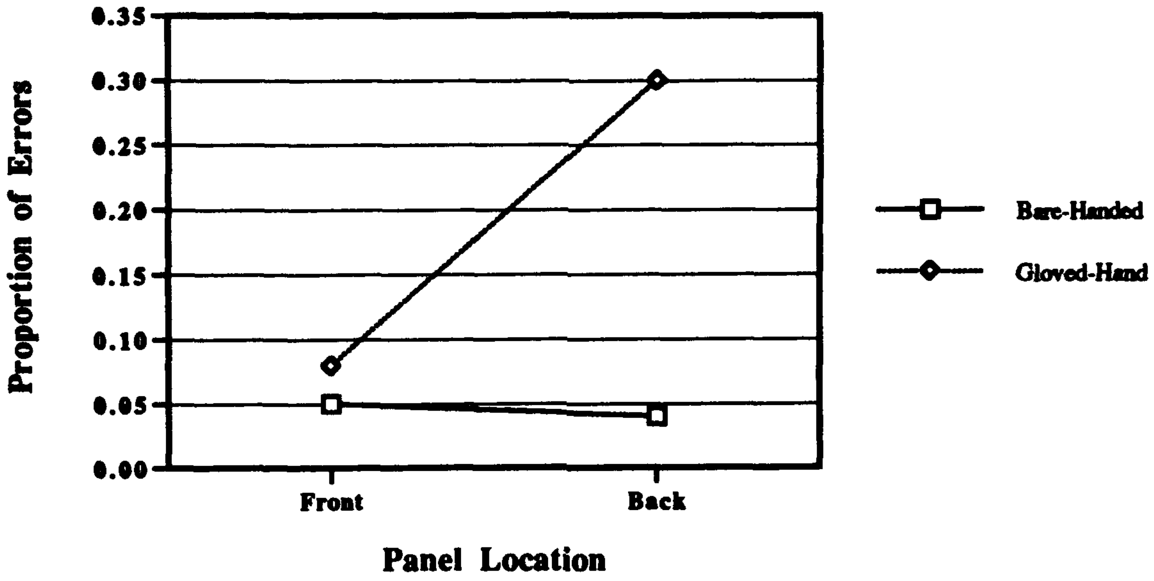


Figure 26. Hand condition by panel location: Butyl and nomex glove assembly, errors-per-opportunity scores.

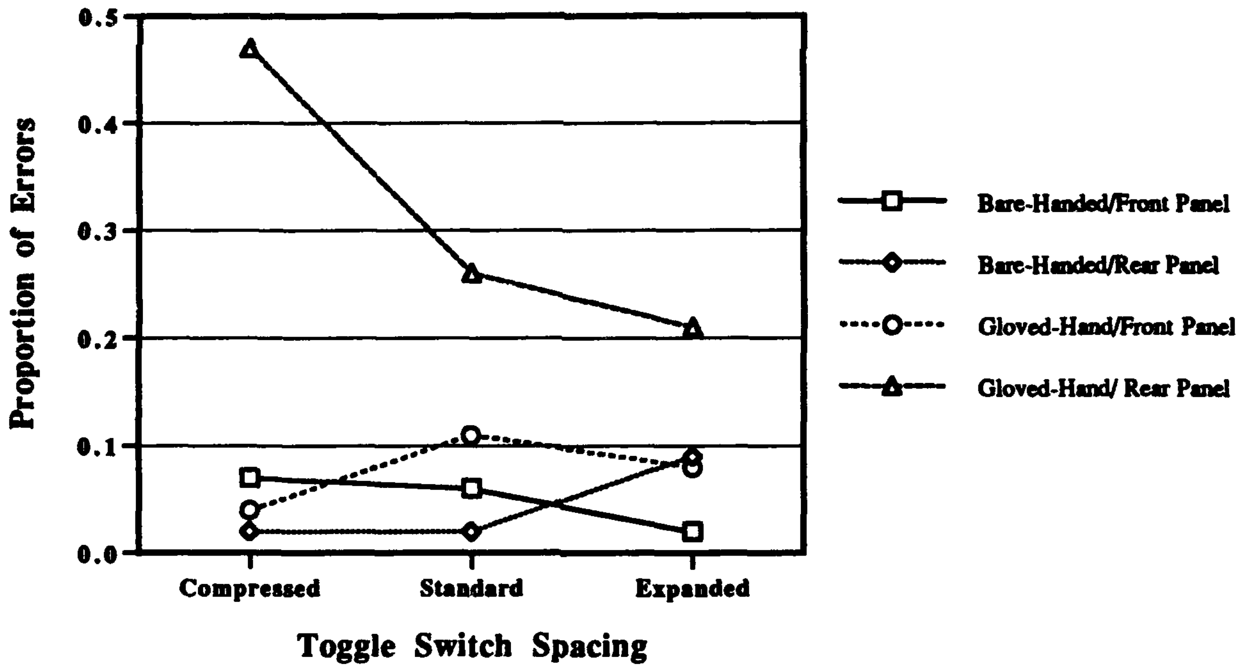


Figure 27. Hand condition by panel location and toggle switch spacing: Butyl and nomex glove assembly errors-per-opportunity scores.

Post hoc analysis of the mean time-of-errors data also determined that the gloved mean time-of-errors scores for the compressed, standard, and expanded spacings were significantly slower than the bare-handed mean time-of-errors scores for the expanded switch spacing (see Table 33).

Analysis of the Fire-Fighting Glove Assembly Data

Significant main effects for the bare-handed data included panel location ($F_{(3,18)} = 7.83$, $p < .001$) and toggle switch spacing ($F_{(6,15)} = 3.15$, $p < .03$). There was one significant three-way interaction, Panel Location x Gender x Toggle Switch Spacing ($F_{(3,18)} = 3.29$, $p < .04$) as shown in Figures 28, 29, and 30. Post hoc analysis was performed by conducting a doubly multivariate ANOVA of each pair combination of toggle switch spacing to determine the source of the switch-spacing effect. Only the analysis of the standard and expanded spacing data revealed significant main effects for switch spacing ($F_{(3,18)} = 3.56$, $p < .04$). These main effects were further investigated by conducting repeated measures ANOVAs of the dependent measures for the standard and expanded spacing data. The results showed that the standard switch spacing yielded significantly more errors per opportunity than the expanded spacing ($F_{(1,20)} = 5.42$, $p < .03$) and significantly slower mean time of error scores than the expanded spacing ($F_{(1,20)} = 9.88$, $p < .005$) (see Table 34).

Table 33

Butyl and Nomex Glove Assembly Data: Mean Bare-Handed and Gloved-Hand Scores

Toggle switch spacing	Bare-handed	Gloved hand
Best time score (s)		
[a]Compressed	2.30	2.63
Standard	2.25	2.47
Expanded	2.06	2.20
Errors-per-opportunity score		
[a]Compressed	.15	.26
[a]Standard	.16	.19
[a]Expanded	.08	.13
Mean time-of-errors score (s)		
Compressed	1.77	2.23
Standard	2.12	2.32
[a]Expanded	1.47	2.30

[a]Front and back panel scores are significantly different.

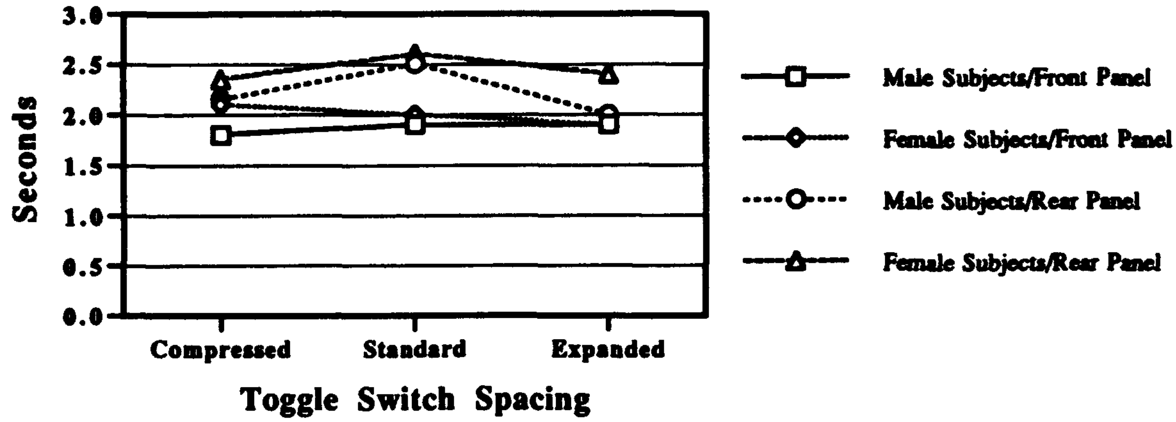


Figure 28. Panel location by gender and toggle switch spacing: Fire-fighting glove assembly, bare-handed best time scores.

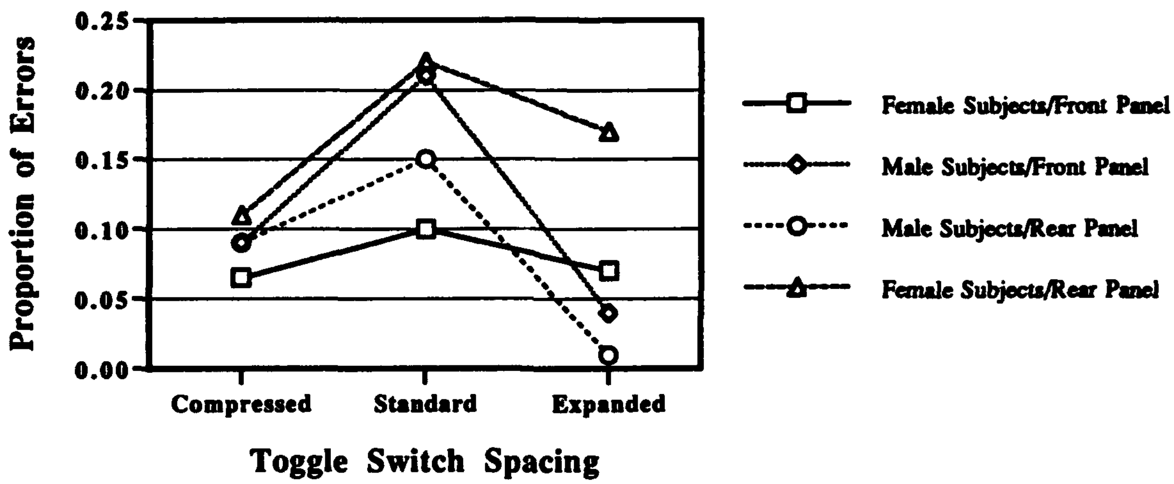


Figure 29. Panel location by gender and toggle switch spacing: Fire-fighting glove assembly, bare-handed errors-per-opportunity scores.

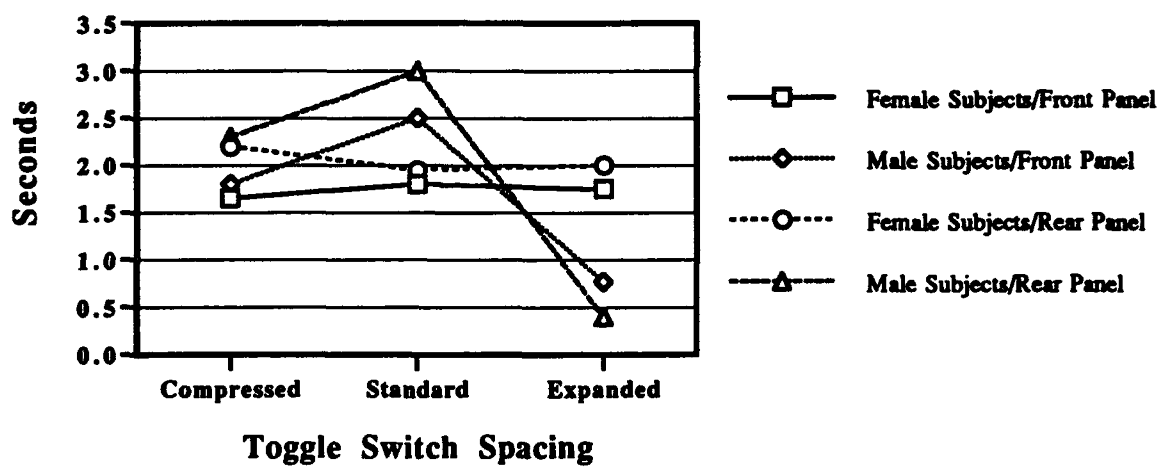


Figure 30. Panel location by gender and toggle switch spacing: Fire-fighting glove assembly, bare-handed mean time-of-errors scores.

Table 34

Fire-Fighting Glove Assembly Data: Mean Bare-Handed Scores for the Compressed, Standard, and Expanded Toggle Switch Spacing

Dependent measures	Switch spacing		
	Compressed	Standard	Expanded
Best time score (s)	2.09	2.26	2.04
[a]Errors-per-opportunity score	.09	.17	.07
[a]Mean time of errors score (s)	1.98	2.28	1.22

[a]Standard switch spacing and expanded switch spacing are significantly different.

A post hoc repeated measures ANOVA of each dependent variable for all pairs of switch spacing was conducted to identify the source of the significant panel location main effects. Univariate analyses showed that the mean best time score for the back panel was significantly slower than the mean best time score for the front panel for the compressed spacing ($F_{(1,20)}$ = 7.70, $p < .01$), the standard spacing ($F_{(1,20)}$ = 5.25, $p < .03$), and the expanded spacing ($F_{(1,20)}$ = 5.52, $p < .03$) (see Table 35).

Table 35

Fire-Fighting Glove Assembly Data: Mean Bare-Handed Scores for Front and Back Panels

Toggle switch spacing	Front panel	Back panel
Best time score (s)		
[a]Compressed	2.25	1.93
[a]Standard	2.58	1.95
[a]Expanded	2.22	1.87
Errors-per-opportunity score		
Compressed	.10	.08
Standard	.18	.16
Expanded	.09	.06
Mean time-of-errors score (s)		
Compressed	2.24	1.72
Standard	2.42	2.15
Expanded	1.20	1.25

[a]Front and back panel scores are significantly different.

Analysis of the gloved data revealed significant main effects for panel location ($F_{(3,18)} = 4.68$, $p < .01$) and toggle switch spacing ($F_{(6,15)} = 5.71$, $p < .003$). Main effects for gender were not significant. Significant interactions included Panel Location x Toggle Switch Spacing ($F_{(6,15)} = 3.92$, $p < .01$) as shown in Figures 31, 32, and 33 and Panel Location x Gender x Toggle Switch Spacing ($F_{(3,18)} = 3.29$, $p < .04$) as shown in Figures 34, 35, and 36. A post hoc doubly multivariate ANOVA of the pair combinations of toggle switch spacing was conducted to determine the source of the significant switch-spacing main effects. The results showed a significant spacing effect for the compressed and expanded spacing data ($F_{(3,18)} = 7.16$, $p < .002$) and the standard and expanded spacing data ($F_{(3,18)} = 5.07$, $p < .01$) but not for the compressed and standard spacing data. The source of the toggle switch spacing effect was explored further by conducting repeated measures ANOVAs of the dependent variables for the compressed and expanded and the standard and expanded spacing data. The results indicated that the errors-per-opportunity scores for the compressed spacing were significantly greater than the errors-per-opportunity scores for the expanded spacing ($F_{(1,20)} = 20.73$, $p < .0002$). Similarly, the standard spacing also had a significantly higher mean errors-per-opportunity score than the expanded spacing ($F_{(1,20)} = 12.53$, $p < .002$) as shown in Table 36.

Post hoc univariate analyses revealed that the back panel best time score was significantly slower than the front panel best time score for the standard switch spacing ($F_{(1,20)} = 17.77$, $p < .0004$) and the expanded switch spacing ($F_{(1,20)} = 7.04$, $p < .02$). Also, the errors-per-opportunity scores were significantly greater for the back panel for the standard spacing ($F_{(1,20)} = 5.20$, $p < .03$). All other panel location effects were not significant as shown in Table 37.

Analysis of the difference data found significant main effects for toggle switch spacing ($F_{(6,15)} = 3.17$, $p < .03$). No other main effects or interactions were significant. The post hoc doubly multivariate ANOVA of the compressed and standard spacing data and the standard and expanded spacing data did not reveal significant main effects for toggle switch spacing. However, significant main effects resulted for the compressed and expanded toggle switch spacing data ($F_{(3,18)} = 5.94$, $p < .005$). Repeated measures ANOVAs were performed on these data to discover the source of this effect. The results showed that the difference between the bare-handed and gloved errors-per-opportunity scores was significantly greater for the compressed switch spacing than the expanded switch spacing ($F_{(1,20)} = 8.44$, $p < .009$).

Analysis of the bare-handed versus gloved-hand data revealed significant main effects for hand condition ($F_{(1,20)} = 19.99$, $p < .0002$) but no significant interactions (see Table 38). Post hoc analysis was performed on the best time scores, errors-per-opportunity scores, and the mean time-of-errors scores using Tukey's HSD test. The results of the best time score analysis showe that the gloved best time score for the compressed spacing was significantly slower than the bare-handed best time scores for the compressed, standard, and expanded spacings. Additionally, the gloved best time score for the standard spacing was significantly slower than the bare-handed scores for the compressed and expanded switch spacings but not the standard switch spacing. The gloved best time score for the expanded spacing was only significantly slower than the bare-handed best time score for the expanded spacing. No other differences were found.

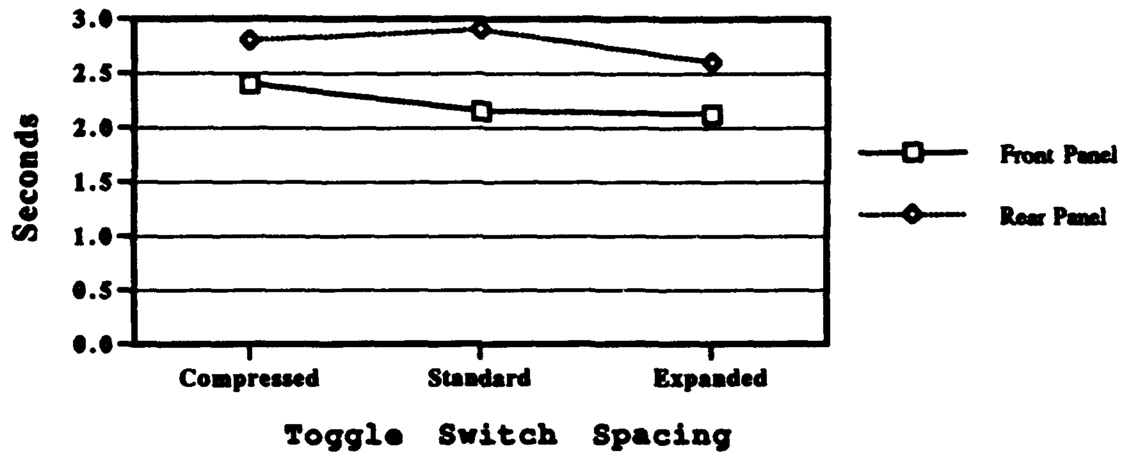


Figure 31. Panel location by toggle switch spacing: Fire-fighting glove assembly, gloved-hand best time scores.

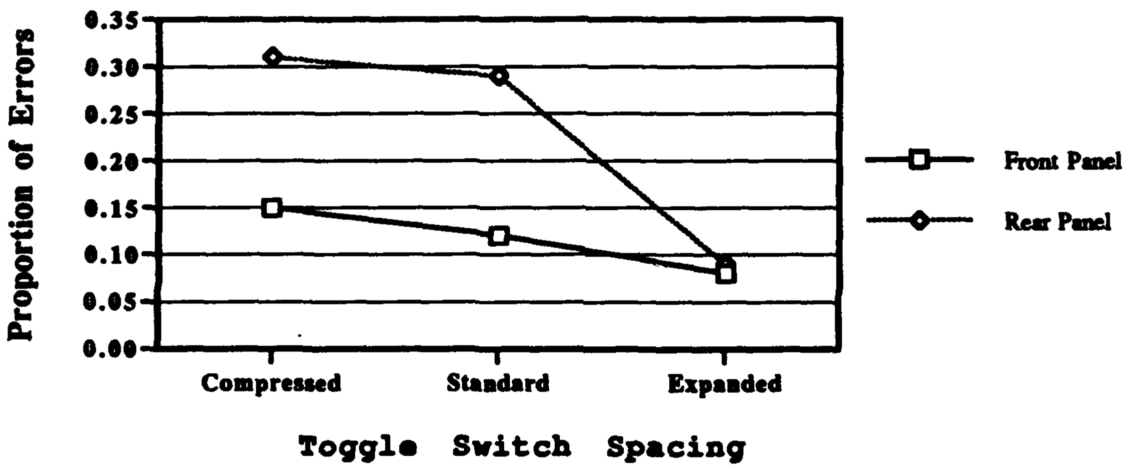


Figure 32. Panel location by toggle switch spacing: Fire-fighting glove assembly, gloved-hand errors-per-opportunity scores.

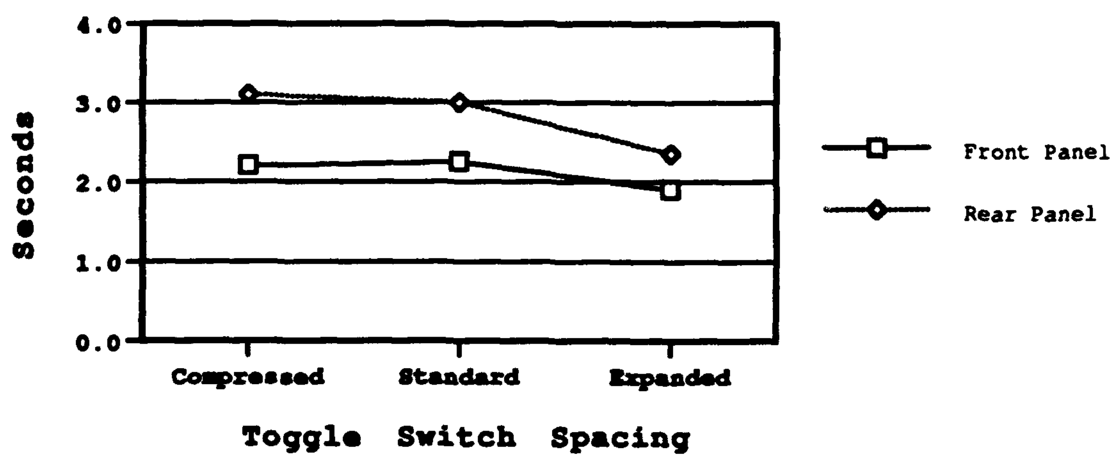


Figure 33. Panel location by toggle switch spacing: Fire-fighting glove assembly, gloved-hand mean time-of-errors scores.

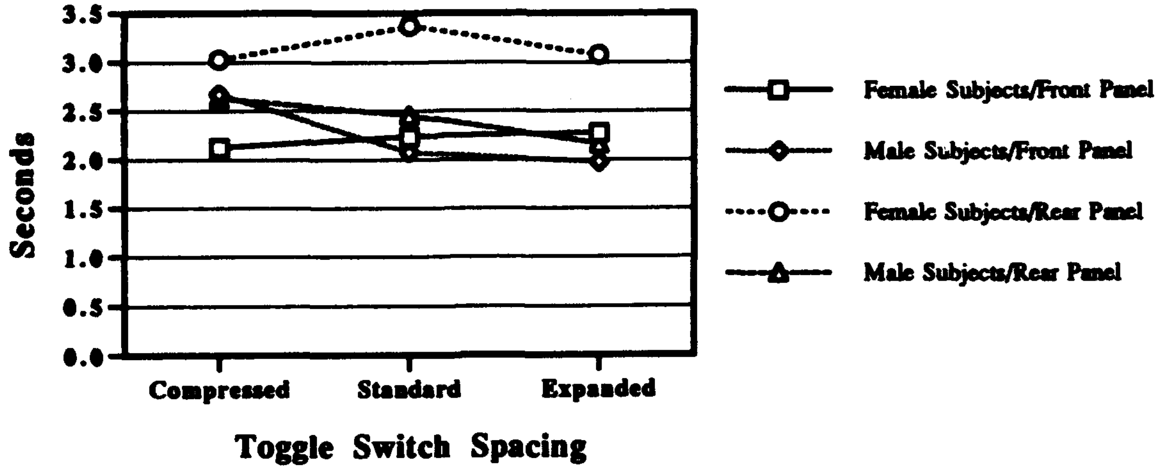


Figure 34. Panel location by gender and toggle switch spacing: Fire-fighting glove assembly, gloved-hand best time scores.

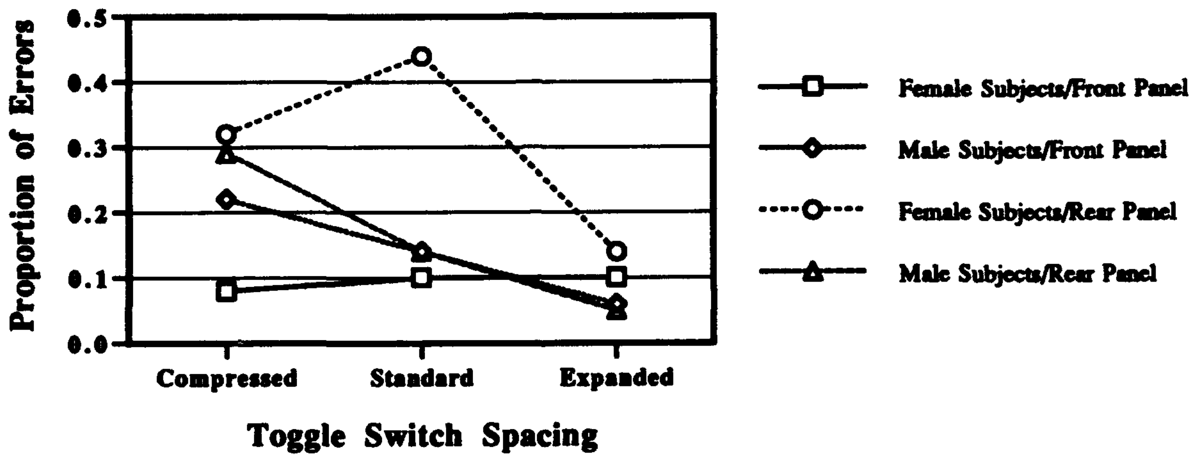


Figure 35. Panel location by gender and toggle switch spacing: Fire-fighting glove assembly, gloved-hand errors-per-opportunity scores.

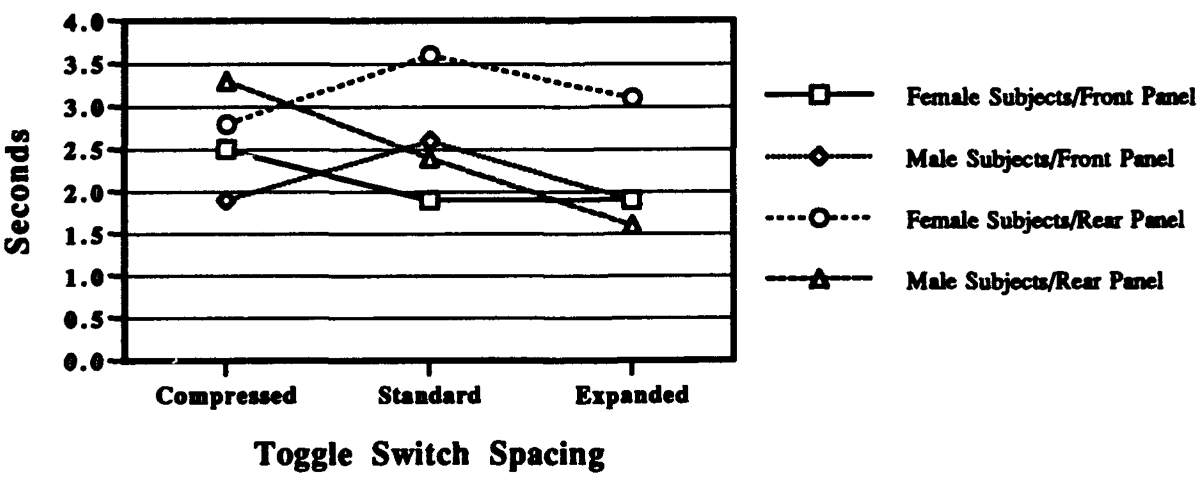


Figure 36. Panel location by gender and toggle switch spacing: Fire-fighting glove assembly, gloved-hand mean time-of-errors scores.

Table 36

Fire-Fighting Glove Assembly Data: Mean Gloved-Hand Scores for the Compressed, Standard, and Expanded Toggle Switch Spacing

Dependent measures	Switch Spacing Compressed	Standard	Expanded
Best time score (s)	2.62	2.52	2.37
[a]Errors-per-opportunity score	.23	.20	.09
Mean time-of-errors score (s)	2.62	2.63	2.11

[a]Compressed and standard spacing scores are significantly different from expanded spacing scores.

Table 37

Fire-Fighting Glove Assembly Data: Mean Gloved-Hand Scores for Front and Back Panels

Toggle switch spacing	Front panel	Back panel
Best time score (s)		
Compressed	2.41	2.83
[a]Standard	2.14	2.91
[a]Expanded	2.12	2.62
Errors-per-opportunity score		
Compressed	.15	.31
[a]Standard	.12	.29
Expanded	.08	.10
Mean time-of-errors score (s)		
Compressed	2.19	3.05
Standard	2.25	3.02
Expanded	1.88	2.34

[a]Front and back panel scores are significantly different.

Table 38

Fire-Fighting Glove Assembly Data: Mean Bare-Handed and Gloved-Hand Scores

Toggle switch spacing	Bare-handed	Gloved hand
Best time score (s)		
[a]Compressed	2.09	2.62
Standard	2.27	2.52
[a]Expanded	2.05	2.37
Errors-per-opportunity score		
[a]Compressed	.09	.23
Standard	.17	.20
Expanded	.07	.09
Mean time-of-errors score (s)		
Compressed	1.98	2.62
Standard	2.28	2.63
[a]Expanded	1.22	2.11

[a]Front and back panel scores are significantly different.

Post hoc analysis of the errors-per-opportunity data showed that gloved scores for the compressed and standard switch spacings were significantly greater than the bare-handed scores for both the compressed and expanded spacings. Also, the gloved score for the expanded spacing was significantly greater than the bare-handed score for the standard spacing. No other differences were found.

Post hoc analysis of the mean time-of-error scores found that the gloved scores for the compressed, standard, and expanded switch spacings were significantly slower than the mean bare-handed score for the expanded spacing. No other significant differences resulted.

Analysis of the Leather and Wool Glove Assembly Data

The analysis of the bare-handed data found no significant main effects or interactions. The gloved data analysis found significant main effects for switch spacing only ($F_{(6,15)} = 5.31$, $p < .004$). The only significant interaction was Panel Location x Toggle Switch Spacing ($F_{(6,15)} = 4.93$, $p < .006$) as shown in Figures 37, 38, and 39.

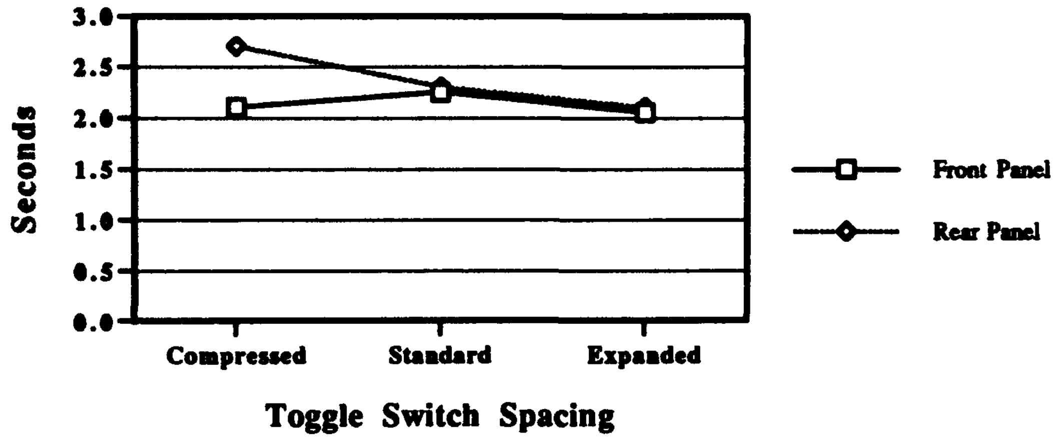


Figure 37. Panel location by toggle switch spacing: Leather and wool glove assembly, gloved-hand best time scores.

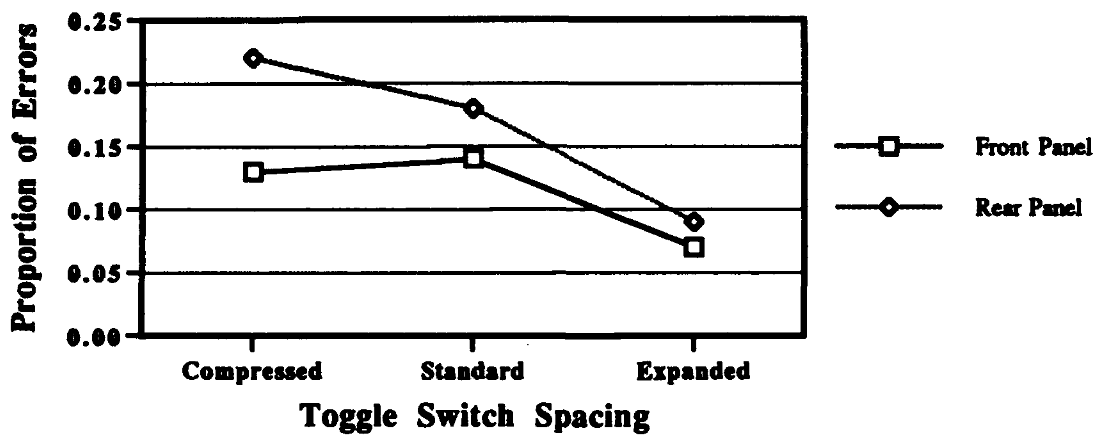


Figure 38. Panel location by toggle switch spacing: Leather and wool glove assembly, gloved-hand errors-per-opportunity scores.

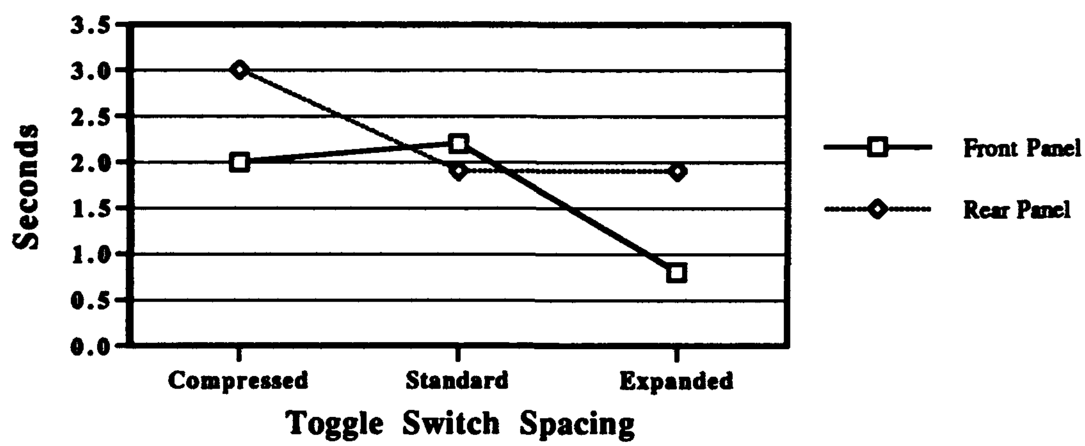


Figure 39. Panel location by toggle switch spacing: Leather and wool glove assembly, gloved-hand mean time-of-errors scores.

A post hoc multivariate ANOVA of the pair combinations of toggle switch spacing was used to determine the source of the toggle switch spacing effect for the gloved data. Analysis of the compressed and expanded spacing data found significant main effects for toggle switch spacing ($F_{(3,18)} = 6.73$, $p < .003$). However, the analyses of the compressed and standard and standard and expanded data did not reveal significant main effects for toggle switch spacing. Repeated measures ANOVAs performed on the compressed and expanded spacing data showed that the mean best time score for the compressed switch spacing was significantly slower than the mean score for the expanded spacing ($F_{(1,20)} = 10.75$, $p < .004$); the mean errors-per-opportunity score for the compressed spacing was significantly higher than the mean score for the expanded spacing ($F_{(1,20)} = 22.10$, $p < .0001$), and the mean time-of-errors mean score was also significantly slower for the compressed spacing than the expanded spacing ($F_{(1,20)} = 10.42$, $p < .004$) (see Table 39).

Analysis of the difference data yielded no significant effects or interactions. Analysis of the bare-handed versus gloved-hand data showed significant main effects for hand condition for best time scores ($F_{(1,20)} = 11.25$, $p < .003$) and errors-per-opportunity scores ($F_{(1,20)} = 12.72$, $p < .002$) but not for mean time-of-errors scores as shown in Table 40. Additionally, the best time score analysis found a significant Hand Condition x Toggle Switch Spacing x Panel Location interaction ($F_{(2,19)} = 5.37$, $p < .01$) as shown in Figures 40, 41, and 42.

Post hoc analysis of the best time scores and errors-per-opportunity scores was conducted using Tukey's HSD test. The results showed that the mean leather and wool glove assembly best time score for the compressed switch spacing was significantly slower than the mean bare-handed best time scores for the compressed, standard, and expanded switch spacings. Also, the leather and wool glove assembly mean best time score for the standard switch spacing was significantly slower than the bare-handed mean best time scores for the standard and expanded spacings but not for the compressed spacing. There were no significant differences between the leather and wool glove assembly mean best time score for the expanded spacing and the bare-handed mean best time scores for all three spacings.

Post hoc analysis of the errors-per-opportunity scores revealed that the leather and wool glove assembly mean errors-per-opportunity score for the compressed switch spacing was significantly greater than the bare-handed mean scores for the compressed, standard, and expanded switch spacings. The leather and wool glove assembly mean score for the standard spacing was significantly greater than the mean bare-handed scores for the standard and expanded switch spacings. No other significant differences between gloved and bare-handed errors-per-opportunity scores were found.

Analysis of the Vinyl Glove Data

Analysis of the bare-handed data found significant main effects for panel location ($F_{(3,18)} = 5.69$, $p < .006$). No other significant main effects or interactions were found. Post hoc repeated measures ANOVAs of all pairings of switch spacing for all dependent variables were performed to investigate the source of the panel location effect. Univariate analyses showed that the back panel mean best time score was significantly slower than the front panel mean best time score for the compressed switch spacing ($F_{(1,20)} = 6.44$, $p < .02$) and the standard switch spacing ($F_{(1,20)} = 5.53$, $p < .03$). Also, the back panel had significantly more errors per opportunity than the front panel for the expanded switch spacing ($F_{(1,20)} = 5.53$, $p < .03$). All other results were not significant (see Table 41).

Table 39

Leather and Wool Glove Assembly Data: Mean Gloved-Hand Scores for the Compressed, Standard, and Expanded Toggle Switch Spacing

Dependent measures	Switch Spacing		
	Compressed	Standard	[a]Expanded
[a]Best time score (s)	2.41	2.29	2.05
[a]Errors-per-opportunity score	0.22	0.14	0.08
[a]Mean time-of-errors score (s)	1.30	2.04	1.66

[a]Compressed and expanded spacing scores are significantly different.

Table 40

Leather and Wool Glove Assembly Data: Mean Bare-Handed and Gloved-Hand Scores

Toggle switch spacing	*Bare-handed*	Gloved hand
Best time score (s)		
[a]Compressed	2.19	2.41
[a]Standard	2.00	2.29
Expanded	2.01	2.05
Errors-per-opportunity score		
[a]Compressed	.06	.22
[a]Standard	.08	.14
Expanded	.07	.08
Mean time-of-errors score (s)		
Compressed	1.70	2.54
Standard	1.88	2.04
Expanded	1.36	1.52

[a]Bare-handed and gloved hand scores are significantly different.

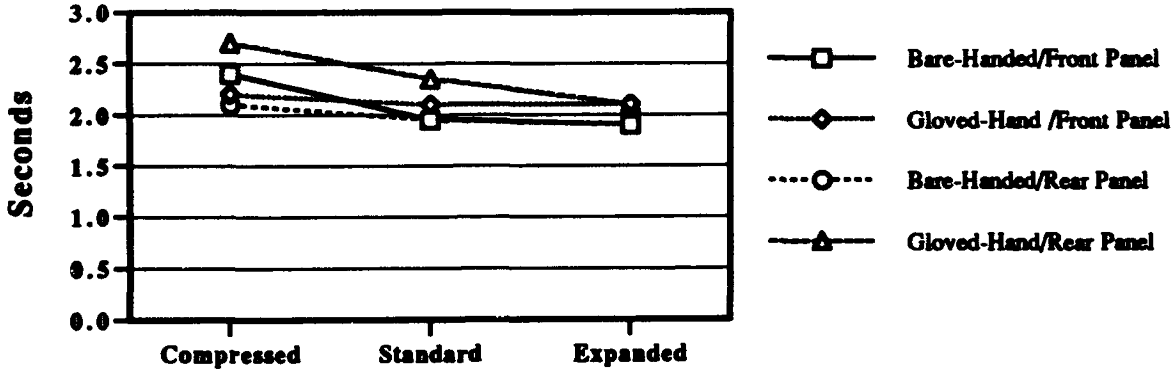


Figure 40. Hand condition by toggle switch spacing: Leather and wool glove assembly, best time scores.

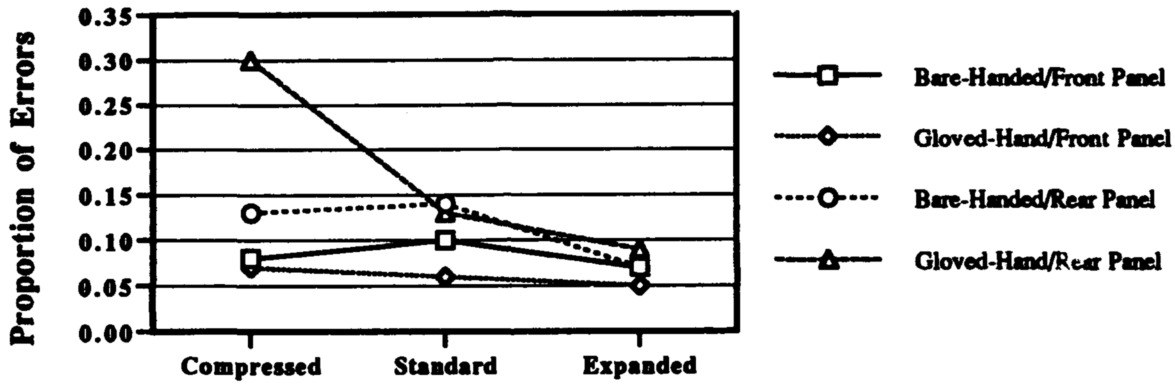


Figure 41. Hand condition by toggle switch spacing and panel location: Leather and wool glove assembly, errors-per-opportunity score.

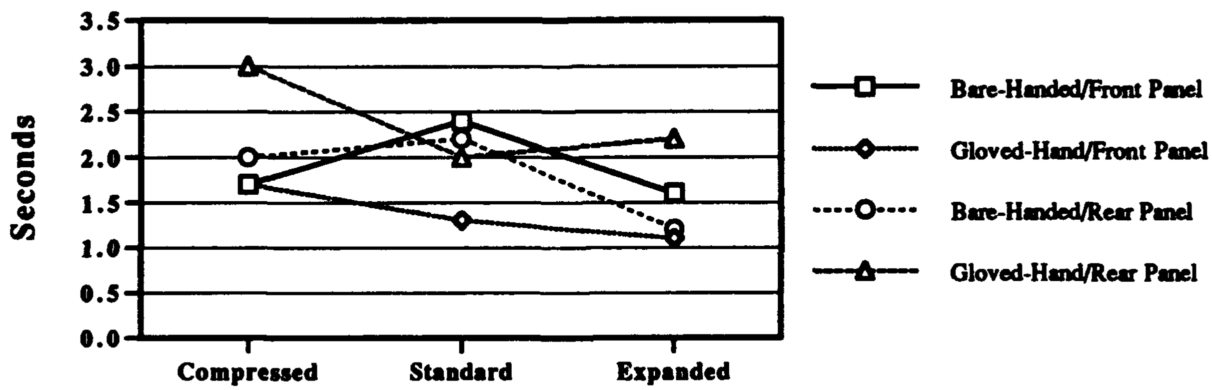


Figure 42. Hand condition by toggle switch spacing and panel location: Leather and wool glove assembly, mean time-of-errors score.

Table 41

Vinyl Glove Assembly Data: Mean Bare-Handed Scores for Front and Back Panels

Toggle switch spacing	Front panel	Back panel
Best time score (s)		
[a]Compressed	1.87	2.46
[a]Standard	1.97	2.47
Expanded	1.93	2.17
Errors-per-opportunity score		
Compressed	.06	.11
Standard	.06	.16
[a]Expanded	.03	.09
Mean time-of-errors score (s)		
Compressed	1.80	2.12
Standard	1.96	2.10
Expanded	1.11	1.85

[a]Front and back panel scores are significantly different.

The results of the gloved data analysis also showed significant main effects for panel location ($F_{(3,28)} = 7.17$, $p < .002$). No other significant main effects or interactions were present. Post hoc repeated measures ANOVAs were conducted to determine the source of the panel location effect. The univariate analyses revealed that the back panel mean best time score was significantly slower than the front panel mean best time score for the compressed spacing ($F_{(1,20)} = 5.28$, $p < .03$), standard spacing ($F_{(1,20)} = 4.48$, $p < .05$), and the expanded spacing ($F_{(1,20)} = 5.28$, $p < .03$). The back panel also had significantly more errors per opportunity than the front panel for the compressed spacing ($F_{(1,20)} = 15.14$, $p < .009$) and the expanded spacing ($F_{(1,20)} = 4.85$, $p < .04$). Additionally, the mean time-of-error scores were significantly slower for the back panel compared to the front panel for the compressed spacing ($F_{(1,20)} = 6.82$, $p < .02$). No other findings were significant as shown in Table 42.

The analysis of the difference data and the bare-handed versus gloved-hand data did not reveal any significant main effects or interactions as shown in Table 43.

Table 42

Vinyl Glove Assembly Data: Mean Gloved-Hand Scores for Front and Back Panels

Toggle switch spacing	Front panel	Back panel
Best time score (s)		
[a]Compressed	1.89	2.32
[a]Standard	1.92	2.44
[a]Expanded	1.83	2.36
Errors-per-opportunity score		
[a]Compressed	.05	.17
Standard	.06	.15
[a]Expanded	.02	.12
Mean time-of-errors score (s)		
[a]Compressed	1.43	2.52
Standard	1.77	2.21
Expanded	.87	1.50

[a]Front and back panel scores are significantly different.

Table 43

Vinyl Glove Assembly Data: Mean Bare-Handed and Gloved-Hand Scores

Toggle switch spacing	Bare-handed	Gloved-hand
Best time score (s)		
[a]Compressed	2.17	2.10
[a]Standard	2.22	2.18
[a]Expanded	2.05	2.10
Errors-per-opportunity score		
[a]Compressed	.09	.11
Standard	.11	.11
[a]Expanded	.06	.07
Mean time-of-errors score (s)		
[a]Compressed	1.96	1.98
Standard	2.03	1.99
Expanded	1.48	1.18

[a]Bare-handed and gloved-hand scores are significantly different.

DISCUSSION

Bare-Handed Data

The bare-handed data were analyzed to determine if there were any preexisting differences between groups and genders that were not because of glove assemblies. There were none. As expected, the location of the panel and the spacing between toggle switches significantly affected performance. The operation of toggle switches on the back panel, which was performed using touch cues only without visual guidance, was significantly slower and less accurate than the operation of switches on the front panel.

The hypothesis that the compressed switch spacing would yield the best bare-handed performance was not supported by this study. The mean speed at which errors were made was significantly slower for the operation of the back panel when the spacing between toggle switches was compressed. The expanded toggle switch spacing yielded a significantly faster, more accurate performance than did compressed or standard toggle switch spacings. No differences were found between compressed and standard spacing.

Gloved Data

Analysis of the gloved data indicated that performance was significantly affected not only by panel location and toggle switch spacing, but also by gender and glove type. In support of the study hypothesis and in agreement with the results of the bare-handed performance data, the back panel yielded significantly slower best time scores and significantly more errors than the front panel. Further, when gloves were worn, the mean speed at which errors were made on the back panel was not only significantly slower when the toggle switch spacing was compressed, but also when the switch spacing was expanded.

The results of the gloved operation on the front panel toggle switches were identical to the bare-handed operation, contrary to the hypothesized outcome. No significant performance difference resulted between the compressed and standard switch spacings; in fact, the expanded spacing resulted in a significantly faster and more accurate performance. Also, errors that were made while operating the expanded panels occurred at speeds significantly faster than those made while operating the compressed and standard panels.

The expanded toggle switch spacing was found to be superior to the compressed and standard spacings for both gloved and bare-handed operation. This finding did not support the hypothesis, based on Fitts' Law, that compressed spacings would result in superior performance because of reduced travel time between switches for bare-handed operators and operators wearing less bulky gloves. The findings did support those of Bradley and Wallis (1959, 1960) that showed operation time and errors decreased when spacings were increased from 15 mm to 25 mm. It is possible that the closer spaced switches impede travel to the next switch in the sequence since less room is available to accommodate the fingers moving between the switches. It is also probable that when the switches are closer, more inadvertent operation errors occur as subjects may unintentionally activate switches adjacent to the target switch. Also, the small switch spacings may make it difficult for subjects to locate a single switch because the closeness of the other switches may require subjects to make more midcourse corrections to reach the target switch. For example, the subjects may have believed that they were operating the second switch in the row when they were really operating the third switch in the row,

not realizing that they had overestimated the travel distance to the next switch. Accordingly, if the subjects had realized the error before activation of the incorrect switch, more submovements would have been required to reach the target switch, thus increasing operation time.

The analysis of the gloved data also revealed a significant Panel Location x Switch-Spacing interaction. This seemed to result from the difference in the mean speed at which errors were made between the front and back panel. This difference was smaller when the toggle switch spacing was standard than when the switch spacing was compressed or expanded. This occurred because the mean time-of-errors score for the subjects in the front panel group was slower when they were operating the standard switches. However, the differences in speed and accuracy between the operation of front and back toggle switches were not greater for the standard spaced toggle switches than for the compressed or expanded spaced switches. This indicates that the subjects in the front panel group made their errors earlier in the trial sequence when the activation time for the switch sequence was relatively longer. This does not appear to have had an impact on their speed or accuracy of operation for this same panel. Consequently, these subjects were able to improve their performance throughout the trial. Therefore, this finding is not practically meaningful.

Analysis of the performance differences between the five different glove assemblies revealed that operation of the compressed toggle switch panels while wearing the vinyl glove was significantly faster than compressed panel operation while wearing the butyl and nomex or fire-fighting glove assemblies. Further, operation of the compressed panels while wearing the vinyl glove was significantly more accurate than performance while wearing the butyl and nomex glove assembly. Also, the mean speed at which errors were made while operating the expanded panels was significantly faster for the subjects wearing the vinyl glove than for subjects wearing the butyl and nomex glove assembly. No other differences between the glove assemblies were found.

These findings supported this study's hypothesis that the bulky glove assemblies would be inferior to the less bulky glove assemblies and that the degradation in performance because of glove bulkiness would be greatest when operating toggle switches with the compressed spacing. The fire-fighting glove and the butyl and nomex glove assembly were the bulkiest of the glove assemblies examined in this study, and the vinyl glove was the least bulky. Additionally, these significant speed and accuracy differences only occurred when the spacing between switches was compressed to 15 mm. These differences were eliminated when the spacing between switches was increased to 20 mm (standard) and 25 mm (expanded). It appears that the combination of great glove bulk and small distances between switches impedes travel time to the target switch and impairs identification and activation of the target switch. This probably caused accidental activation of adjacent switches. The differences between gloves regarding the mean speed at which errors were made were only demonstrated when the switch spacing was expanded. This probably occurred because of the poor performance of all gloves when the spacing was compressed and standard. Because of the overall poor performance of the gloves, there was little variability between them concerning the mean speed at which errors were made. When performance improved with the expanded spacing, the differences between gloves could be found. These differences indicate that subjects wearing the fire-fighting glove made errors early in the trial sequence. Subjects wearing the vinyl glove did not have to make the same adjustments to gloved operation and did not make errors early in the trial sequence.

The hypothesis that performance with gloves of greater tenacity would be superior to gloves of little tenacity was not supported by the results of this experiment. The butyl glove had the greatest tenacity, followed by the vinyl glove, the fire-fighting glove, and the leather glove having had the least amount of tenacity. Because of the marked difference in bulk, it was expected that there would be significant performance differences between the leather and wool glove assembly and the butyl glove assemblies, and the leather and wool glove assembly and the vinyl glove. However, the leather and wool glove performance did not differ from the vinyl and butyl glove performances. In contrast to Bradley's (1969b) study, glove tenacity did not appear to play a major role in the performance of the toggle switch operation task.

These findings did support Bradley's (1969b) conclusion that glove pliability did not significantly influence the operation of toggle switches. The vinyl glove was the most pliable of the glove assemblies studied, the butyl glove assemblies were the next most pliable, and the leather and wool glove assembly the least pliable. If pliability were a major factor affecting toggle switch operation, significant performance differences would be expected between the vinyl and leather and wool glove assemblies and little difference would be expected between the vinyl glove and the butyl glove assemblies; however, this did not occur.

Although the fire-fighting glove was found to have more bulk than the butyl and nomex glove assembly, it did not result in a greater degradation of performance. The fire-fighting glove generated the second highest errors-per-opportunity score for operation of the compressed toggle switches and the second slowest mean speed at which errors were made for operation of the expanded switches. However, subject performance while wearing the fire-fighting glove did not significantly differ from subject performance while wearing the vinyl glove. This might be because of the differences in glove snugness. The fire-fighting glove had a smaller circumference range for each glove size than did the butyl glove, and it was able to fit a greater percentage of the subjects. In contrast, the butyl glove had a poor fit for male subjects with large hand circumferences. Bradley (1969b) determined that glove snugness would improve the gloved operation of most controls. The butyl and cotton glove did yield better performance than the fire-fighting glove, although this was not statistically significant. It may be that gloves with greater bulk can provide better performance with better snugness. Of all the glove characteristics studied, glove bulk appeared to have the greatest effect on toggle switch operation, with this effect mediated to some extent by glove snugness.

The results of the gloved data analysis also indicated that gloved male subjects performed the toggle switch operations significantly faster than female subjects when the switch spacing was either standard or expanded. When the switch spacing was compressed, the speed of gloved operation between male and female subjects did not differ. There were no gender differences concerning the accuracy of operation or the mean speed at which errors were made across switch spacings. Additionally, the findings of this study showed that the difference between male and female subjects' performances varied according to the location of the toggle switch panel. Specifically, the difference in operation speed between genders was greater for the back panel than for the front panel. When operating switches on the front panel, female subjects made fewer errors and had a slower speed at which errors were made than male subjects. When operating switches on the back panel, male subjects made fewer errors and had a slower speed at which they made these errors than female subjects.

Since gender differences in performance were not found when the subjects operated the toggle switches with the bare hands, it seemed that the gloves degraded the performance of female subjects more than male subjects. One possible explanation for this is the difference in glove fit. Glove snugness was more difficult to obtain for the smaller female subjects' hand sizes. The smaller female subjects had loose-fitting gloves, which may have impeded finger movements, necessitating more movements and a greater expenditure of energy, slowing operation time. Also, a loose-fitting glove degrades tactile sensitivity and dexterity to a greater degree, which required the female subjects to perform more submovements to ensure that the target switch was identified and grasped. This greater reduction in tactile feedback and dexterity would also explain why these speed differences between male and female subjects were greater when operating toggle switches on the back panel, which was performed without visual feedback to guide their movements. The female subjects may have been able to make fewer errors than male subjects when operating switches on the front panel because female subjects slowed their operation in response to the visual indications that their performance was inaccurate at higher speeds. The male subjects had the advantage (they used less degraded dexterity and tactile feedback to compensate for the lack of visual feedback and were able to perform more accurately than female subjects) when operating back switches. Male subjects made errors at slower speeds and were able to improve their accuracy as the trial progressed.

No speed differences were found between gloved male and female subjects when the toggle switches were compressed. This was probably because the combination of glove bulk and small switch spacing impaired performance to the extent that variability of glove snugness was not evidenced. While the increased spacing between switches relieved difficulty for male subjects operating in a crowded condition, it did not relieve difficulty for female subjects with loose-fitting gloves.

Another possible explanation is that gender differences genuinel_ existed but were not demonstrated during the bare-handed switch operation task. The bare-handed task was so easy that ceiling effects may have obscured a genuine difference in performance between male and female subjects. Adding gloved operations to the task may have increased performance difficulty just enough so that preexisting gender differences in motor performance were exposed.

Difference Data

Bare-handed scores were subtracted from gloved-hand scores to obtain difference scores. These difference scores were used to quantify the deterioration in performance induced by hand wear while manipulating the toggle switches during the varying conditions of this experiment.

The results indicated that differences in speed and accuracy between gloved and bare-handed operators were significantly greater when the toggle switch panel was located behind the operator than when it was located in front of the operator. However, this effect only occurred when the toggle switch spacing was compressed. The performance degradation because of gloves did not differ between operating the back and front panel with standard and expanded switches. It is likely that the decreased tactile feedback and dexterity because of the gloves is much more degrading to performance without visual feedback. When the subject faced the toggle switches, the visual feedback compensated for the reduced tactile feedback and decreased dexterity. This enhanced degradation was only evident when the switch spacing was compressed. When subjects had more travel distance between switches and more room to grasp

a single switch, they were able to compensate for the reduction in tactile feedback and dexterity when visual feedback was absent. The close-position switches generated more inadvertent activation errors as well as the misidentification of target switches because of overestimating the travel distance between toggles. The subjects were less able to sense the presence of two separate toggle switches because of their reduced 2-point threshold.

This difference in degradation magnitude of gloved performance did not exist when operating the compressed and standard panels or when operating standard and expanded panels. This difference suggests that switch spacing needs to be varied by more than 5 mm to increase or reduce the degree of glove degradation in the accuracy of performance.

Analysis of the difference scores did not reveal any significant differences in the degradation of the speed of gloved operation. The results showed that for all three switch spacings, gloves degraded the speed of bare-handed operation to the same degree. This suggests that within the switch spacing parameters of 15 mm to 25 mm, varying the distance between switches by 10 mm can influence the degree that gloves degrade the accuracy of operation, but it cannot influence the degree that gloves degrade operation speed. It was possible that the degradation caused by gloves in operation speed was less affected by the distance between switches than was the accuracy of operation. The spacing differences examined in this study were not large enough to produce differences in the speed of gloved operation. If it were true that the glove bulk slows operation by impeding movement and impairing target identification, then it is likely that this degradation remains constant and is independent of switch spacing within the range studied. A distance greater than 25 mm between switches would possibly reduce the speed degradation because of gloves. The greater distance might allow the gloved hand and fingers to travel more freely and smoothly between switches and provide sufficient distance so specific switch locations could easily be identified. It is not surprising that accuracy proved to be a more sensitive measure of glove effects than speed. A subject could maintain a rate of speed while unknowingly be committing more errors. If a subject were not aware of making errors because they were inadvertent or because of the reduced sensory feedback, he or she would not believe it would be necessary to intentionally slow his or her speed while operating the compressed toggle panel. It is probable that any decrease in the operator's speed was because of the physical constraints of the glove, which is why this degradation remained constant and was not mediated by the subject's knowledge of performance errors.

The significant Panel Location x Spacing interaction resulted because the greatest difference between front and back panel location difference scores occurred when the toggle switch spacing was compressed. Thus, the degradation in performance caused by gloves was greatest while the subjects were operating compressed toggle switches on the back panel. This effect was found for speed and accuracy of operation and for the mean speed at which errors were made. This finding supported this study's hypothesis as both the back panel location and the gloved operation with compressed toggle switches were expected to degrade performance. It was expected that the combination of these conditions would exacerbate performance degradation because of the added effects of zero visual feedback, decreased tactile feedback, loss of dexterity, and small distances between switches. The loss of accuracy while wearing gloves did not differ between the operation of front and back panels when the switch spacing was expanded. In the two other cases, back panel performance was degraded by the wearing of gloves to a greater extent than front panel performance. With the increased spacing, subjects were able to reduce errors caused by inadvertent operation and misidentification of the target switch when operating switches without visual feedback.

The analysis of the difference data also indicated that the difference in operation speed between the bare-handed and fire-fighting glove was significantly larger than the difference in operation speed between the bare-handed and the vinyl glove. This effect only occurred when the toggle switch spacing was compressed. No other significant differences between glove assembly difference scores were found. Thus, the five different glove assemblies studied in this experiment degraded performance equally with the one exception: When the spacing between the switches was compressed, the fire-fighting glove slowed operation speed significantly more than the vinyl glove. No differences were found between the three military glove assemblies studied. This finding also supported the study hypothesis that the more bulky glove assemblies would degrade performance to a greater extent than the less bulky glove assemblies.

Bare-Handed Versus Gloved-Hand Data

Gloved operation on the expanded panel switches was significantly slower than bare-handed operation of these switches, but gloved operation did not differ from bare-handed operation of the compressed and standard panels. A significant Glove x Hand-Condition interaction also resulted. This occurred because the decline in operation speed produced by the butyl and cotton, butyl and nomex, and leather and wool glove assemblies was similar while the fire-fighting glove degraded the speed of bare-handed operation to a much greater extent. However, the vinyl glove did not degrade bare-handed operation speed. In fact, when the subjects were wearing the vinyl glove, the operation speed was slightly faster than the bare-handed operation speed. As hypothesized, the bulkiest glove degraded performance the most while the vinyl glove with relatively no bulk and great tenacity allowed the subject to operate the toggle switches at a slightly faster speed.

The accuracy measures behaved in similar ways. Gloved operation of the compressed and standard panels resulted in proportionately more errors than bare-handed operation of the compressed, standard, and expanded panels. Further, gloved operation of the expanded panel was significantly more accurate than bare-handed operation of the standard panel, but accuracy did not differ from the bare-handed operation of the compressed and expanded panels. The significant Hand-Condition x Panel-Location interaction resulted because the greatest accuracy difference between the gloved and bare hand occurred when the toggle switches were located behind the subject. Additionally, the significant Hand-Condition x Spacing interaction appeared because the greatest accuracy difference between gloved and bare-handed operation occurred when the toggle switch spacing was compressed, while the smallest accuracy difference occurred when the toggle switch spacing was expanded. The significant Hand-Condition x Spacing x Panel-Location interaction occurred because the most inaccurate performance occurred when the toggle switch spacing was compressed, the switch panel was located behind the subject, and the subject was wearing a glove. These findings supported the hypothesis that the combination of glove bulk and the smallest switch spacing would produce inferior performance and that the lack of visual feedback would degrade performance. The combined effects did indeed produce the worst performance.

Additional results of the bare-handed versus gloved-hand data analysis showed that gloved operation of the compressed and standard toggle switches yielded a significantly slower mean speed at which errors were made than the bare-handed operation of the compressed and expanded toggle switches; however,

this speed did not differ from the bare-handed operation of the standard switches. The mean speed at which errors were induced was significantly higher when the subjects were wearing gloves and operating the expanded toggle switches than when the subjects were operating the standard switches with their bare hands; however, this speed did not differ from the bare-handed operation of compressed and expanded switches. Thus, the fastest error-free performance resulted from the bare-handed operation of the compressed or expanded switches, or the gloved operation of the expanded switches. These results were because of the comparably slow speed at which errors were made when the subjects were operating the standard panel with their bare hands. These subjects committed some errors early in the trial but then were able to recover and operate the switches at faster speeds without making a disproportionate number of errors; their mean time-of-errors score increased as a result. Thus, it appeared that subjects were able to operate the expanded panel of switches error free with the gloved hand at speeds similar to bare-handed operation. The increased spacing between switches reduced the performance impairment caused by glove bulk and reduced tactile feedback and dexterity.

Individual Glove Data

Each glove was analyzed separately to further determine differential effects on toggle switch operation.

Butyl and Cotton Glove Assembly

When the subjects performed bare-handed, the speed and accuracy scores of this group did not differ significantly across panel spacings.

When these same subjects were wearing the butyl and cotton glove assembly, operation of the back panel toggle switches was slower than operation of the front panel toggle switches not only when the switch spacing was compressed, but also when the spacing was standard and expanded. It was concluded that this speed degradation was due, at least in part, to wearing of the butyl and cotton glove assembly. Speed degradation most likely resulted from the increased difficulty of identifying target switches without visual feedback when tactile feedback has also been reduced by the glove assembly. Additionally, even though there were no differences in the accuracy of bare-handed operation between the two panel locations, when wearing the glove assembly, the subjects committed proportionately more errors when the compressed switch panel was behind them as opposed to in front of them. There were no accuracy differences between the gloved operation of front and back toggle switches when the spacings were standard and expanded. Similarly, the combination of closely spaced switches with the loose-fitting butyl and cotton glove assembly is believed to have made target switch identification difficult. Activation of incorrectly identified switches was likely to have occurred.

The butyl and cotton glove assembly had more bulk than the vinyl glove but less than the other three assemblies included in this study. Further, it had the greatest tenacity of all gloves tested. Although this glove assembly fit loosely on the hands of most subjects, this did not seem to significantly degrade bare-handed performance. It is possible that low bulk and high tenacity are much more important glove qualities than snug fit while operating toggle switches.

Butyl and Nomex Glove Assembly

Analysis of bare-handed performance indicated that the operation of switches on the back panel compared to the front panel was significantly slower, resulting in proportionately more errors and a slower mean speed at which these errors occurred. However, these effects only resulted when the switch spacings were standard or expanded and did not occur when the switch spacing was compressed.

When the subjects wore the butyl and nomex glove assembly, significant gender effects emerged. Specifically, when operating the compressed switches, female subjects committed errors at slower speeds than male subjects; when operating the standard switches, female subjects operated the switches more slowly than male subjects; and when operating the expanded switches, female subjects committed more errors than male subjects. Thus, it appeared that the butyl and nomex glove assembly degraded the performance of female subjects to a greater extent than male subjects since these differences did not result when the subjects operated the switches with their bare hands. Because the female subjects' inferior performances were not focused on any single dimension, this may represent a general difficulty in performing this task while wearing the butyl and nomex glove. Since this effect was not found for the butyl and cotton glove assembly, it may be that the combination of marked bulk with looseness of fit eroded the female subjects' performances. The butyl and cotton gloves fit the female hand much more loosely than the male hand. Since looseness of fit reduces dexterity and tactile sensitivity, it may have added to the effects of glove bulk by impairing performance to a measurable degree. Looseness of fit may not have impaired female subjects' performances more than male subjects' performances when operating switches wearing the butyl and cotton glove assembly because that glove assembly had relatively little bulk.

Additionally, the differences in performance between the front and back panels were not the same for gloved operation as for bare-handed operation. Toggle switches with all three spacings were operated more slowly when they were behind the subject. Also, a significantly greater proportion of errors were made when operating the compressed and standard switches on the back panel. The mean speed at which errors were made was significantly slower on the back panel but only when the spacing was compressed. Differences in the accuracy and the speed at which errors were made were not significant between the front and back panels when the switch spacing was expanded. The back panel scores improved with the expanded spacing because the greater distances between switches compensated for the lack of visual feedback in the presence of decreased tactile feedback and dexterity.

The findings from the butyl and nomex glove data also indicated a significant Panel-Location x Gender interaction. The differences between female and male performances were greatest when the subjects were operating the toggle switches on the back panel. Thus, the lack of visual feedback degraded female subjects' performances to a greater extent than male subjects' performances. It is believed that the combination of glove bulk and loose fit for the female subjects explains this finding, since the bare-handed data did not reveal this interaction.

The butyl and nomex glove assembly degraded the accuracy of operation of the back panel switches much more than the operation of front panel switches. Again, this effect only occurred when the panel spacing was compressed or standard and not when the spacing was expanded. This appears to support the hypothesis that the combination of glove bulk and close switches would impair performance to a greater extent.

The butyl and nomex glove assembly degraded the speed of both front and back panel operations to the same extent. Thus, it appeared that the subjects did not reduce their speed while making errors. They were probably not aware of their inaccurate performance because of no visual feedback and reduced tactile feedback and dexterity.

When the bare-handed outlier scores were replaced with mean scores, the analysis of the data also indicated that bare-handed operation of the toggle switches was significantly more accurate than operation of the switches while wearing the butyl and nomex glove assembly. The proportion of errors committed while operating the panels was significantly greater when wearing this glove assembly than when operating the switches bare-handed. The results again showed that the accuracy differences between gloved and bare-handed operations were greatest when the panel was located behind the subject. Thus, the butyl and nomex glove assembly degraded the accuracy of operation to a much greater extent without visual feedback. The poorest performance was produced by the combination of the butyl and nomex glove assembly, the compressed switch spacing, and the back switch panel. As stated previously, operation of compressed switches without visual feedback and with degraded tactile feedback appeared to result in more inadvertent operation errors and a greater likelihood of misidentifying the target switch.

Because of the conservative alpha level, operation speed and the mean speed at which errors were made while subjects wore the butyl and nomex glove assembly were not found to be significantly slower than bare-handed operation, despite their significance at the .02 alpha level. Post hoc analyses of these scores found that the speed of gloved operation of the compressed switches was significantly slower than the speed of bare-handed operation of the compressed, standard, and expanded switches. Additionally, the speed of gloved operation of the standard switches was significantly slower than the speed of bare-handed operation of the expanded switches. Operation speed when wearing the butyl and nomex glove assembly did not differ from bare-handed operation speed when the toggle switches were standard or expanded. In contrast, the speed at which errors were made did not differ between gloved and bare-handed operation when the switch spacing was compressed or standard; however, when the switch spacing was expanded, gloved operators made errors at slower speeds. Consequently, the butyl and nomex glove assembly affected the accuracy of operation to a much greater extent than it affected operation speed. Further, the larger switch spacing alleviated the glove effect on speed. The gloved hand was able to move between switches without as much interference. The subjects were probably able to maintain their rate of speed because of marked tenacity of this glove assembly. This contention was supported by the lack of difference between the butyl and cotton glove assembly and the bare hand. The butyl and cotton glove assembly had exactly the same tenacity as the butyl and nomex glove assembly, but the butyl and cotton glove had less bulk. Thus, the presence of this bulk appeared to degrade accuracy.

Fire-Fighting Glove Assembly

When the subjects were operating the toggle switches bare-handed, performance was significantly less accurate with standard spacing than with expanded spacing. Similarly, the mean speed at which errors were made was significantly slower with standard spacing than with expanded spacing. The operation of the back panel toggle switches was slower than the operation of front panel regardless of switch spacing.

The bare-handed data analysis revealed a significant Panel-Location x Spacing x Gender interaction that appeared to be because of speed and accuracy differences between male and female subjects. In general, female subjects operated the switches more slowly than male subjects. Speed of operation did not differ between male and female subjects operating the expanded front switches but did differ markedly between male and female subjects operating the expanded back switches. Although speed differences between the genders were eliminated with expanded spacing when the switches were located in front of the subjects, they increased significantly when the expanded switches were located behind the subjects. The three-way interaction resulted from accuracy differences between genders. When operating the compressed and standard switches on the front panel, female subjects made proportionately fewer errors than male subjects, but when operating the expanded front switches, male subjects made proportionately fewer errors than female subjects. In contrast, the female subjects were consistently less accurate than male subjects when operating switches on the back panel; this accuracy difference greatly increased when the switch spacing was expanded. Further, male subjects operating switches on the back panel were more accurate than both genders operating switches on the front panels. The greatest gender differences occurred when the switch spacing was expanded, particularly on the back panel. The male subjects performed particularly well when the switch spacing was expanded. These exceptional scores most likely explain why this gender difference resulted.

The gloved data showed fewer effects than the bare-handed output data. This probably was because of the overall degradation in performance that resulted when wearing the fire-fighting glove across all switch spacings. The results showed that while subjects wore the fire-fighting glove, operation of the compressed and standard toggle switches was significantly less accurate than operation of the expanded switches. The accuracy of operation did not differ between the compressed and standard switch spacings. Further, there were no differences in operation speed or the mean speed at which errors were made across switch spacings.

The gloved data analysis revealed that the back panel toggle switches were operated more slowly than the front panel toggle switches when the switch spacings were standard or expanded, but not when they were compressed. The mean speed at which errors were made did not differ between front and back panel locations regardless of the switch spacing.

The degradation accuracy of the fire-fighting glove operation was much greater when the switch spacing was compressed than when it was expanded. These findings once again support the hypothesis that the combination of the bulkier gloves and the compressed switch spacing would yield the poorest performance. Although wearing the fire-fighting glove degraded the operation accuracy of the expanded switches, the degree of this degradation was significantly less than the degree of degradation that occurred with compressed spacing.

Performance while wearing the fire-fighting glove was significantly inferior to bare-handed performance in both speed and accuracy, regardless of switch spacing. As with the other glove groups, the expanded spacing appeared to make it possible for the subjects to correctly identify and activate the target switch despite the decreased tactile feedback and loss of dexterity.

Additionally, the subjects committed errors at significantly slower speeds while wearing the fire-fighting glove as compared to bare-handed operation. The fire-fighting glove was detrimental to performance. Even

though the best performances occurred when the subjects were operating the expanded switches bare-handed, wearing the fire-fighting glove resulted in slower operation speeds and more errors made at these slower speeds. Although performance improved with expanded spacing, 25 mm was not enough to equate bare-handed and gloved performances. Subjects needed to slow their operating speed to perform the task. However, this strategy only improved performance when the switch spacing was expanded, and did not help when the spacing was standard or compressed. Despite the slower speed, the subjects were still making as many errors as they did when operating the switches with their bare hands at faster speeds. Since this glove had slightly more bulk but much less tenacity than the butyl and nomex glove assembly, it appeared that the lack of tenacity was a major contributor to the slow speed of operation. The subjects' fingers slipped off the switches, resulting in more submovements before activating the target switch. The increased bulk made it difficult for the subjects to know if they had the target switch firmly in their grasp, prompting repeated attempts to grasp the switch more firmly which further slowed the speed of switch activation. These results support the contention that high glove tenacity allows the subject to maintain a rate of operation similar to bare-handed operation. Subjects wearing the butyl and nomex glove assembly were able to firmly grasp and activate the switch despite the bulky glove because of its greater tenacity compared to the fire-fighting glove.

Leather and Wool Glove Assembly

When subjects were operating the toggle switches with their bare hands, performance was not significantly affected by switch panel location, switch spacing, or operator's gender. However, when the subjects were wearing the leather and wool glove, operation of the compressed toggle panel was significantly slower and less accurate than the operation of the expanded toggle panels. Errors were made at significantly slower speeds when the switches were compressed than when they were expanded.

A significant Panel-Location x Spacing interaction occurred when the leather and wool gloves were worn. This interaction was because of the decline in performance that occurred when the toggle switches were behind the subjects and performance was markedly greater when the switch spacings were compressed than standard or expanded. The greatest difference in speed and accuracy between the front and back panel locations resulted when the spacing was compressed. Also contributing to this significant interaction was the difference between the front and back panels in the mean speed at which errors were made. Since the subjects operating the front standard spacing panel did not make more errors or operate at slower speeds than the subjects operating the back standard spacing panel, this indicates that the subjects operating the front panel made errors earlier in the trials. These subjects must have been able to improve their performances and operate the switches quickly and correctly.

Accuracy was also degraded by wearing the leather and wool glove assembly. While gloved, the subjects made proportionately more errors when operating the compressed switches. Again, the accuracy of gloved operation of the expanded switches did not significantly differ from bare-handed operation of the compressed, standard, or expanded switches. The speed at which errors were made when the subjects were wearing this glove did not differ from bare-handed operation.

A significant Panel-Location x Spacing x Hand-Condition interaction occurred when the leather and wood glove was used. When subjects wore this glove assembly, speed and accuracy differences were greatest when subjects were operating the compressed back switches. Gloved operation of the back compressed switches was much slower and less accurate than gloved operation of the front compressed switches. However, gloved operation of the front standard toggle switches was only slightly more accurate than the gloved operation of the back toggle switches and yielded a slower mean speed at which errors occurred. These effects were the basis of the three-way interaction observed.

It seems that the subjects operating the front panel had some difficulty maneuvering the standard switches both with the glove on or off. They made proportionately more errors at slower speeds of operation. Although these differences were not significant, the poorer performance appeared to have contributed to the interaction. Thus, these differences are unique to the subjects operating the front panel and are most likely not of practical importance. The most meaningful contributing factor to this significant interaction is that, as expected, the worst performance resulted when the subject was wearing the leather and wool glove assembly and was operating compressed switches on the back panel.

In contrast to gloved operation, bare-handed operation of the back compressed switches was faster than bare-handed operation of the front compressed switches. Conversely, speed of operation of the front standard and expanded switches was much faster than bare-handed operation of the back standard and expanded switches. The largest differences concerning the number and speed of errors between bare-handed operation of front and back switches resulted when the switch spacing was standard. The subjects operating the front toggle switches made proportionately more errors at a slower speed than the subjects operating the back switches; these differences were exaggerated when the switch spacing was standard. The decline in performance because of these factors was alleviated when the switch spacing was 5 mm greater than current military standards.

Although the leather and wool glove had the least amount of tenacity, performance improved with expanded switch spacing. Since the glove also had less bulk than the fire-fighting and butyl and nomex glove assemblies, this suggests that glove tenacity affects the accuracy of performance to a greater degree when there is great glove bulk. The results also suggest that tenacity has a much more important role when the glove loosely fits the hand. Although the butyl glove was the most difficult glove to fit to the smaller- and medium-sized hands, the leather and wool glove assembly fit more snugly than the fire-fighting glove. Increased glove tenacity allowed the subjects to "stick" to the switch, giving them the impression that the switch was firmly grasped despite the bunched palm material.

Vinyl Glove Assembly

Bare-handed operation of the back panel was significantly slower than bare-handed operation of the front panel. More errors were made when the switch spacings were standard or compressed. Bare-handed operation of the front and back panels did not differ when the spacing was expanded.

The performance differences between the operation of front and back panel switches were somewhat more extensive when the subjects were wearing the vinyl glove. Regardless of the switch spacing, the operation of the back panel switches was significantly slower than operation of the front panel switches. Additionally, proportionately more errors were made when operating the back switches with the compressed and expanded spacings. Gloved operation of the back panel compressed switches also resulted in slower speeds at which errors occurred. No other significant differences were found between the gloved operation of front and back switches.

The difference data analysis yielded no significant results which indicated that differences between gloved and bare-handed operation did not vary across panel locations, switch spacings, or genders. Further, no significant differences were found between gloved and bare-handed operation. This finding does not support the study hypothesis that performance while wearing the light vinyl glove with great tenacity will be superior to bare-handed operation. Although gloved performance scores were often better than bare-handed performance scores, these differences were not significant. It was initially believed that the vinyl glove would improve bare-handed operation performance because of the increased tenacity. Since this did not happen, this finding supported the contention that glove tenacity may be more of a determinant of toggle switch operation performance than glove bulk.

Operation of the back panel switches was somewhat more degraded when the subjects were wearing the vinyl glove. This might have been because of reduced hand flexibility for individuals with larger hands.

Since this glove did not degrade tactile sensitivity, this factor could not contribute to the decline in speed and accuracy of operation of the back panel switches. However, this glove fit like a second skin and was somewhat restrictive to very large hands, despite the manufacturer's claim that "one size fit all." However, overall, gloves with little bulk and great tenacity do not markedly degrade toggle switch operation.

SUMMARY

This research effort was designed to improve military specifications for toggle switch spacing with gloved operators.

Bare-handed operation of the toggle switches is quicker and more accurate when the switches are spaced 25 mm apart, rather than 15 mm or 20 mm apart. Operating unseen toggle switches located behind the operator is slower and less accurate than the operation of toggle switches located in front of the operator, regardless of the toggle switch spacing.

Performance of the toggle switch task while wearing gloves is substantially more accurate and faster when the switches are spaced 25 mm apart rather than 15 mm or 20 mm apart. The 25-mm spacing yields a particular improvement in operating the switches located behind the subjects. These switches are operated entirely by feel.

The operation of toggle switches while wearing a thin vinyl glove is faster and more accurate than switch operation while wearing a butyl and nomex glove assembly, the standard military NBC glove for cold climates. Three other gloves were studied: a military butyl and cotton assembly for NBC use in hot climates, a military leather and wool assembly, and a civilian fire-

fighting glove with high bulk and low tenacity. All three gloves are similar to the butyl and nomex assembly in that switch operation is degraded, and the 25-mm spacing is superior to the closer spacings.

Details about the specific performance deficits of these five gloves, the interaction of glove characteristics (bulk, suppleness, and tenacity) and the three switch spacings studied are reported at length in the extended Results and Discussion section of this report.

Gloved male subjects are able to operate toggle switches spaced 20 mm and 25 mm apart significantly faster than gloved female subjects, particularly when the switches are located behind the operator. These gender-linked results seem to be caused by problems of hand size and glove fit, not gender-linked differences in ability.

Wearing gloves degraded operating the unseen back panel switches more than operating the front panel switches. Wearing gloves degrades operating switches spaced only 15 mm apart to a much greater extent than operating switches spaced 25 mm apart. Accordingly, the greatest performance degradation results when gloves are worn to operate switches spaced 15 mm apart and located behind the operator. The very bulky fire-fighting glove degrades bare-handed operation significantly more than the thin vinyl glove when the toggle switches are spaced 15 mm apart.

The analysis of the bare-handed versus gloved-hand data indicates that when the subjects are wearing gloves, they operate the toggle switches significantly more slowly, regardless of the spacing between switches. The fire-fighting glove causes the greatest decline in operation speed while the vinyl glove caused the smallest decline. Bare-handed operation of the toggle switches spaced 15 mm and 20 mm apart is more accurate and errors are made at faster operation speeds than gloved operation of these same switches. However, when the switches are 25 mm apart, the accuracy and the speed at which errors are made did not differ between gloved and bare-handed operation.

Individual glove analyses reveals that operating the toggle switches while wearing the gloves with the least bulk and the greatest tenacity (the commercial vinyl glove and the standard military NBC butyl and cotton glove assembly) does not significantly differ from operating the switches bare-handed. However, operation of the toggle switches while wearing the other glove assemblies does differ from bare-handed operation.

The butyl and nomex glove assembly has marked bulk and great tenacity. When wearing this glove assembly, subject performance is significantly less accurate compared to operating the toggle switches bare-handed. However, the speed of gloved operation is less affected.

The fire-fighting glove has the greatest bulk and relatively little tenacity. Although operation of the toggle switches with the 15- and 20-mm spacing is significantly less accurate while wearing the fire-fighting glove compared to bare-handed, the accuracy of operating switches with the 25-mm spacing does not differ between bare-handed and gloved operations.

The standard military leather and wool glove assembly has substantial bulk and has the least tenacity. The results indicate that when the toggle switch spacings are 15 mm and 20 mm, operating the switches while wearing the leather and wool glove assembly is significantly slower and less accurate than operating switches bare-handed. However, operating the toggle switches with the 25-mm spacing does not differ in terms of speed and accuracy between bare-handed and leather and wool glove assembly.

The standard 20-mm spacing between toggle switches meets the MIL-STD-1472D spacing requirements. However, this spacing does not produce the best performance. For those tasks that meet the following requirements (a) toggle switches are operated in sequence, (b) toggle switches meet the MIL-STD-1472D specifications for operation with heavy hand wear, and (c) the speed and accuracy of operation are a high priority; spacing between toggle switches of at least 25 mm (5 mm farther) apart than the current military standard is recommended. Continued study is needed to determine if this spacing should be even greater to achieve the fastest and most accurate performance possible. Although both 20- and 15-mm spacing produced poorer speed and accuracy results than 25-mm spacing, there is no significant difference between them. If speed and accuracy were not a high priority task requirement and the other task requirements were met, then the toggle switch spacing could be reduced by at least 5 mm, to 15 mm, without degrading performance compared to toggle switches spaced 20 mm apart. A further study is also needed to determine if switches could be spaced closer than 15 mm. Additionally, it is recommended that glove bulk be minimized as much as possible to enhance performance. The speed and accuracy of operating toggle switches while wearing a bulky glove can be improved by glove snugness and increased glove tenacity.

One limitation of this study is that the spacing requirements of gloved operations regarding other types of switches has not been investigated. Future studies should investigate the most common combinations of toggle switches with other types of controls.

REFERENCES

Adolfson, J. A., & Berghage. T. E. (1974). Performance and perception under water. New York: Wiley

Berkhout, J., Anderson, G., McCleerey, M., & Granaas, M. (1992). Gloved operator performance study control panel dimensions for gloved operation, study I: Push buttons (Technical Memorandum 7-92). Aberdeen Proving Ground, MD: U.S. Army Human Engineering Laboratory.

Bradley, J. V. (1961). A methodology for glove evaluation. Perceptual and Motor Skills, 12, 373-374.

Bradley, J. V. (1969a). Effect of gloves on control operation time. Human Factors, 11(1), 13-20.

Bradley, J. V. (1969b). Glove characteristics influencing control manipulability. Human Factors, 11(1), 21-36.

Bradley, J. V., & Wallis, R. A. (1959). Spacing of on-off controls. II: Toggle switches (WADC-TR-58-475). Wright-Patterson Air Force Base, OH: Wright Air Development Center.

Bradley, J. V., & Wallis, R. A. (1960). Spacing of toggle switch on-off controls. Engineering and Industrial Psychology, 2, 8-9.

Bullock, M. I. (1974). The determination of functional arm reach boundaries for operation of manual controls. Ergonomics, 17(3), 373-388.

Carlingswitch, Inc. (1988). Innovation by design. Plainville, CT: Author.

Chapanis, A. & Kinkade, R. G. (1972). Design of controls. In H. P. Van Cott & R. G. Kinkade (Eds.), Human engineering guide to equipment design (pp. 345-379). Washington, DC: U.S. Government Printing Office.

Diffrient, N., Tilley, A. R., & Harman, D. (1981). Humanscale 1b manual. Cambridge: Massachusetts Instate of Technology.

Eastman Kodak Company (1986). Ergonomic design for people at work, volume 2. New York: Van Nostrand Reinhold.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. Journal of Experimental Psychology, 47(3), 381-391.

Gordon, C. C., Chruchill, T., Clauser, C. E., Bradtmilr, B., McConville, J. T., Tebbets, I., & Walker, R. A. (1989). 1988 anthropometric survey of U.S. Army personnel: Summary statistics interim report (Technical Report 89/027). Natick, MA: U.S. Army Natick Research, Development, and Engineering Center.

Ivergard, T. (1989). Handbook of control room design and ergonomics. London: Taylor and Francis.

Kirk, R. D. (1982). Experimental design (2nd ed.). Belmont, CA: Wadsworth.

Tabachnick, B. G., & Fidell, L.S. (1989). Using multivariate statistics (2nd ed.). New York: Harper & Row.

U.S. Department of Defense (1989). Military standard 1472D. Washington, DC: Author.

Woodson, W. E. (1981). Human factors handbook. pp. 84, 753-756. New York: McGraw-Hill.

APPENDIX A

EXPERIMENT DESCRIPTION AND CONSENT FORM

EXPERIMENT DESCRIPTION AND CONSENT FORM

GLOVED OPERATOR STUDY

INFORMED CONSENT FORM

You are invited to participate in the Gloved Operator Performance study at the USD Human Factors Laboratory. Your participation is voluntary. You must be over 18 years old.

The purpose of this study is to measure how much interference is caused by wearing a glove when operating certain kinds of machinery and control panels. If you agree to take part, you will go through a training period without wearing gloves, and then a further training and test period while wearing gloves. The results will provide information on the amount of skill lost when wearing gloves, and will provide some suggestions for designing machines and gloves so that there is as little loss as possible.

The study will require about two hours of your time. There is no risk involved, and you will not be asked to work at full strength, or in a fatigued condition.

You will be awarded extra credit in your psychology class for participating. The number of extra credit points will be determined by the class professor.

You may stop working in this study at any time and leave. If you don't finish the two hour assignment, the extra credit will be pro-rated.

Your scores will be kept confidential, and your name will not be associated in any way with the results.

You may ask questions about the study at any time. We appreciate your taking part. If you agree to do so, please sign this form. You will be given a copy for your own records.

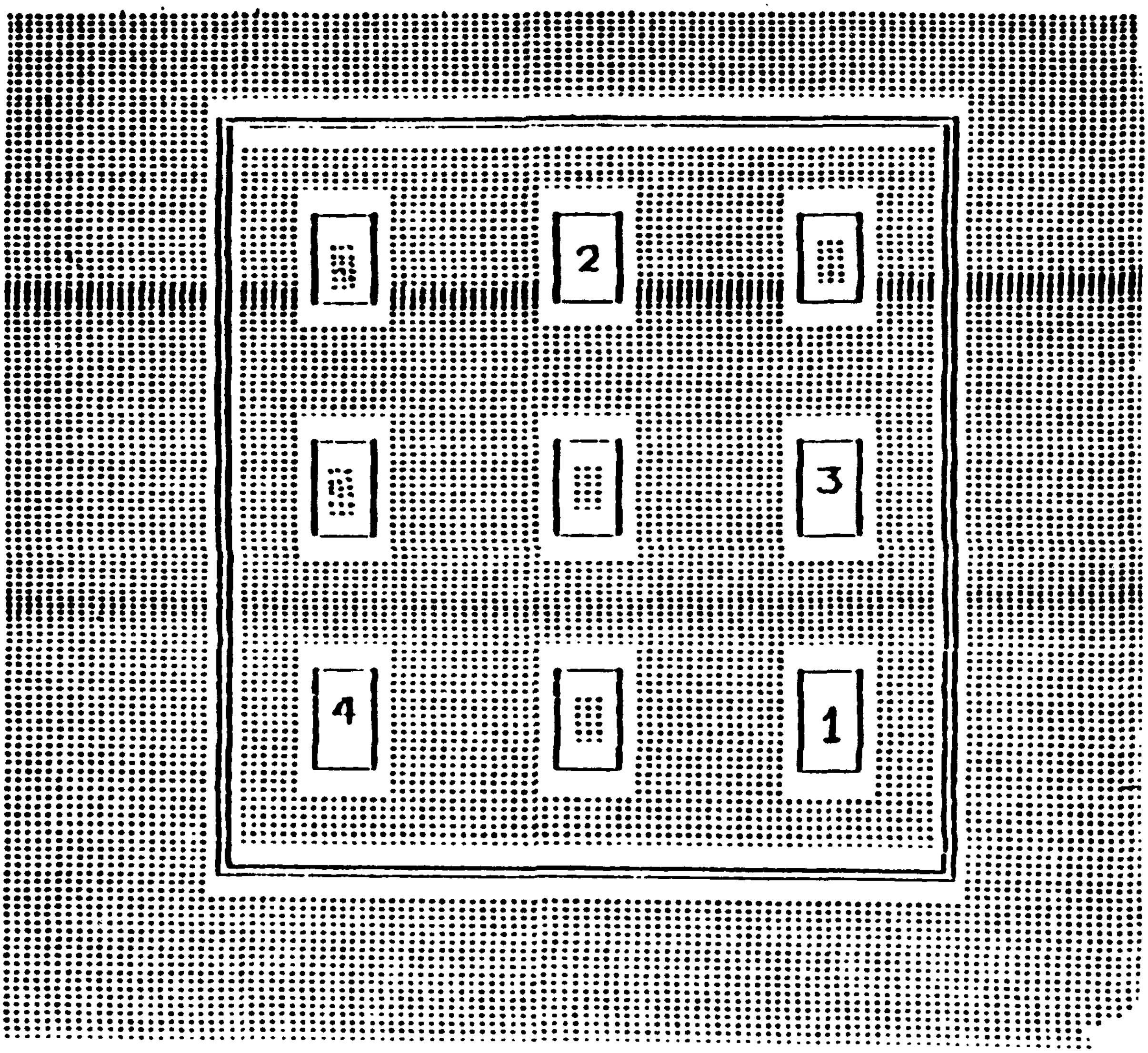
Jan Berkhout
Principal Investigator
677-5295

Subject signature	Age	Date
Researcher		Date

APPENDIX B

EXAMPLE OF EXPERIMENTAL DIAGRAM

EXAMPLE OF EXPERIMENTAL DIAGRAM



APPENDIX C

ACTUAL GLOVE MEASURES

Table C-1

Actual Glove Measures

Glove Type/Size	Hand Circumference	3rd Digit Length	Wrist to 2nd Digit
Butyl/Cotton			
Small	232	78*	182
Medium	233	75	195
Large	250	80	200
Nomex			
8	200	90	196
9	200	90	201
10	210	95	207
11	220	95	211
Leather/Wool			
3	190	80	165
4	202	85	172
5	220	87	186
Fire Fighter**			
Small	235	93	197*
Medium	265	94	196
Large	273	96	212
X-Large	278	99	215

* This measure is larger for the small size than the medium.

** These are the unadjusted measures.

APPENDIX D

HAND DIMENSION RANGES

Table D-1

Hand Dimension Ranges

Glove Type/Size	Hand Circumference	3rd Digit Length	Wrist to 2nd Digit
Butyl/Cotton			
Small	-244	-82	-191
Medium	221-245	71-79	185-205
Large	238-	76-	190-
Nomex			
8	-210	-95	-206
9	190-210	86-95	191-211
10	200-221	90-100	197-217
11	209-	90-	203-
Leather/Wool			
3	-200	-84	-173
4	192-212	81-89	163-181
5	209-	83-	177-
Fire Fighter			
Small	-204	-93	-203
Medium	205-228	86-95	183-203
Large	213-235	87-97	198-218
X-Large	217-	90-	200-

APPENDIX E

INSTRUCTIONS FOR FRONT PANEL TASK

INSTRUCTIONS FOR FRONT PANEL TASK

The monitor in front of you will present diagram like this one. The diagrams will show nine rectangles that correspond to the panel of nine toggle switches in front of you. As soon as a diagram appears, press down the four toggles indicated by the diagram. Press the toggles in the order indicated by the numbers on the diagram. The toggle labelled '1' first, '2' second, '3' third, and '4' fourth. If you press a wrong toggle, ignore the mistake and press the next toggle in the sequence of four.

After you press the four toggles, wait for a new diagram to appear on the screen. A certain amount of time will be allowed to press the four toggles, and the diagrams will remain on the screen even if you have already pressed four toggles. When time has expired for a diagram, a tone will sound and the diagram will disappear, and no more toggle presses will be recognized for that diagram. If you are not finished pressing the toggles for the previous diagram, leave it unfinished and wait for the next diagram. A new diagram will appear several seconds after the tone.

. . . . Press any toggle to continue . . . .

While waiting for the next diagram to appear, place your hand on your lap. Leave your hand there until a beep and a message on the monitor tell you to "Position your hand..." You should then place your hand near the toggles.

When you press the toggles, press them as quickly as you can without making a mistake. Be sure to press the toggles all the way down so that each toggle activation will be recognized, but do not keep the toggle held down as that will cause an error.

Each time you press four toggles correctly, the time limit for the following diagram will be slightly less than the previous one. If you make a mistake, a new diagram will appear with the same time limit as the previous one. Eventually you will not have enough time to press four toggles correctly. After you make three mistakes in a row, the task will stop. You will have a series of practice trials and a test trial for each of the three different panels. You may ask questions about the instructions during practice. Do you have any questions now?

....Press any toggle to begin the tasks....

APPENDIX F

INSTRUCTIONS FOR BACK PANEL TASK

INSTRUCTIONS FOR BACK PANEL TASK

The monitor in front of you will present diagrams like this one. These diagrams will show nine rectangles that correspond to the panel of nine toggle switches located behind you, to you lower right side. The top row of switches on the diagram corresponds to the bottom row of switches on the panel. The middle row of switches on the diagram corresponds to the middle row of switches on the panel. The bottom row of switches on the diagram corresponds to the top row of switches on the panel. It is as if the diagram was hung upside down behind you.

As soon as a diagram appears on the screen, flip up the four toggles indicated by the diagram. Flip up the toggles in the order indicated by the numbers on the diagram. The toggle labelled '1' first, '2' second, '3' third, and '4' fourth. Each toggle switch will immediately return to its original position upon being flipped up into the 'on' position. If you flip up a wrong toggle, ignore the mistake and flip up the next toggle in the sequence of four.

When you flip up the toggles, flip them as quickly as you can without making a mistake. Be sure to flip the toggles all the way up so that each toggle activation will be recognized, but do not keep the toggle held up as that will cause an error.

....Flip up any toggle to continue....

After you flip up the four toggles, wait for a new diagram to appear on the screen. You will be allowed a certain amount of time to flip up the four toggles, and the diagrams will remain on the screen even if you have already completed the task. When time has expired for a diagram, a tone will sound and the diagram will disappear, and no more toggle presses will be recognized for that diagram. If you are not finished flipping up the toggles for the previous diagram, leave it unfinished and wait for the next diagram. A new diagram will appear several seconds after the tone.

While waiting for the next diagram to appear, place your hand on your lap. Leave your hand there until a beep and a message on the monitor tell you to "position your hand..." You should then position your hand either near or resting lightly on the toggles, whichever you prefer. When the diagram appears, you need to press the correct toggles in order WITHOUT looking at the panel of switches.

....Flip up any toggle to continue....

Each time you flip up the four toggles correctly, the time limit for the following diagram will be slightly less than the previous one. If you make a mistake, a new diagram will appear with the same time limit as the previous one. Eventually you will not have enough time to flip up four toggles correctly. After you make three mistakes in a row, the task will stop. You will have a series of practice trials and a test trial for each of three different panels. You may ask questions about the instructions during practice. Do you have any questions now?

....Flip up any toggle to begin the tasks....

APPENDIX G

RESULTS OF BARE-HANDED DATA ANALYSIS

RESULTS OF BARE-HANDED DATA ANALYSIS

The main effect for panel location was significant

$$(\underline{F}_{(3,98)} = 10.69,\ \underline{p} < .002),$$

the toggle switches on the back panel taking more time to operate than those on the front panel. Also, the main effect for switch spacing was significant,

$$(\underline{F}_{(6,95)} = 3.71,\ \underline{p} < .002),$$

the toggle switches with the expanded spacing taking less time to operate than both the compressed and standard spaced toggle switches.

The main effects for gender and assigned glove were not significant, and so the five groups may be considered truly equal in barehanded ability on these tasks. The mean best-time scores, errors-per-opportunity, and mean-time-of-error scores for each panel location, switch spacing and gender are shown in Tables 8, 9, and 10, for each of the groups assigned to particular gloves, but performing bare-handed. There was one significant interaction, assigned-glove-group by panel-location

$$(\underline{F}_{(12,160)} = 1.99.\ \underline{p} < .02),$$

as shown in Figures 2 - 10.